PRESIDENT 1925-1926

Lafayette, Manchester, photo.

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CORRIGENDA TO VOLS. 61 AND 63.

Vol. 61, page 534, Equation (24): For " H " read " $2H$ ".
,, page 534, Equation (25): For " H " read " nH ".
,, page 543: Equation (37) should read " $H = nI^2R_1$ ".
,, page 567, Equation (58): In the first part of the denominator, for " nI^2r_4 " read " nI^2R_1 ".

Vol. 63, page 1087, col. 2, line 21: for " 2 cm " read " D cm ".
,, page 1168, col. 1: For " Maclean, A. B.,
" Electricity in mines, (D), 554.
" Obituary notice. 1156."
read " Maclean, Andrew B. Obituary notice. 1156.
" MacLean, Archibald B. Electricity in mines. (D), 554 ".

THE JOURNAL OF

The Institution of Electrical Engineers

VOL. 64.

INAUGURAL ADDRESS

By R. A. CHATTOCK, President.

(*Address delivered before* THE INSTITUTION, *22nd October*, 1925.)

It was with a feeling of pleasure and a consciousness of the great honour you have bestowed upon me personally that I learnt of my selection as President of this great Institution, and I thank you very sincerely. It is worthy of note that this is the first occasion on which a municipal electrical engineer has been selected to fill this high position, and I feel therefore—and I know that my brother municipal engineers agree with me—that my selection also reflects a great honour upon the municipal side of the electricity supply industry, which has now reached such large dimensions and is continuing to grow at such an accelerating rate.

It is an illuminating fact that two chief engineers of large electricity supply undertakings have been selected during the past session and the present session to this high office, and I cannot help thinking that the intention underlying this was largely influenced by the fact that at the present time His Majesty's Government is interesting itself in the present position and the future of this particular section of the industry, and in consequence the subject is becoming one of great public interest. The views, therefore, of engineers of supply undertakings are perhaps of especial interest at the present time.

My predecessor, Mr. W. B. Woodhouse, in his admirable address a year ago, discussed at considerable length the progress that has been made in all branches of the electricity supply industry. I do not therefore propose to traverse the ground that he covered so exhaustively, but I will confine myself to one or two matters in connection with that industry which I think are of special interest just now, and which will bear being elaborated.

REPORT OF THE ELECTRICITY COMMISSION.

This Report, embodying as it does such a vast amount of statistical matter in connection with the generation and supply of electrical energy in this country, is, in my opinion, a most valuable book of reference for supply engineers. Its compilation has obviously involved an enormous amount of work, and the thanks of the industry are due to the Commissioners for preparing and issuing it.

It is satisfactory to know that these Reports will in future be issued annually and without the delay that has necessarily occurred in connection with the first volume, because if information of this kind is to be acted upon it is essential that it should be available as soon as possible.

The general review deduced from the statistics and embodied in the Report is particularly valuable, including as it does average figures for the whole country dealing with the growth of the industry, the operation of the undertakings, and the financial results. It is gratifying to know that these figures are year by year improving, and that the cost of production is coming down, with the natural result that the cost to the consumer is being lessened.

Although it is early days yet to suggest that this is a result of the establishment of the Electricity Commission, yet it is, I think, obvious that the improvement year by year has been materially assisted by the general policy of the Commissioners, whose avowed object has been to provide for the country a " cheap and abundant supply."

The sympathetic advice and assistance which the Commissioners bring to bear upon the numberless schemes submitted to them, based as such advice is upon high technical knowledge and tempered with sound financial judgment, are most helpful in promoting that co-ordination of the industry from which only the best results are to be anticipated.

Such results cannot be obtained all at once. Considerable time is required to reconcile the many interests involved, and to ensure that existing developments are

properly utilized and the money already spent upon them is not wasted.

The task that the Commissioners are carrying out, involving as it does such a heavy responsibility and requiring the consideration of so much detail, can only be regarded as colossal. One hears complaints that things are not moving fast enough, and that after six years only one Joint Authority has so far come into existence. In my opinion, far better and more lasting progress can be made by going slowly and thoroughly considering each step. I should like to suggest to the Commissioners in a spirit of friendly criticism that, when far-reaching and costly changes are contemplated, a free and frank discussion with the interests involved would be of far greater value to the commercial community than the production of a cut-and-dried proposal that has to stand antagonistic criticism, which might quite easily have been disarmed by reasonable compromise.

Coal.

The available statistics go to show that 95 per cent of the units generated in this country are derived from steam-operated generating plant, and that practically all this energy is derived from coal or coal products. A comparison of the performance of these stations year by year is a very helpful stimulant to economy in their operation, but it seems to me that to compare the performance of steam-operated stations on a "pounds of coal per unit generated" basis only is rather misleading. What we are all aiming at, and what the Commissioners' statistics are designed to promote, is to produce and distribute units of electricity as cheaply as possible.

A station using fuel of a very poor calorific value at a low price per ton can produce a unit of electricity quite as cheaply as, and even at a lower cost than, a station using a high-priced fuel of high calorific value, although the fuel consumption per unit and the thermal efficiency of such a station may compare unfavourably with those of the station using the expensive fuel.

Again, if the distillation of coal proves to be a commercial possibility, from 30 to 70 per cent more weight of coal will have to be handled to produce a given quantity of electricity, and whilst it may pay handsomely to adopt this process, the number of pounds of coal used per unit will of course compare very unfavourably with the figures obtained in a station burning coal to destruction.

I think, therefore, that a better method of comparison would be the cost, rather than the weight, of the fuel per unit generated, and this cost would have to take into account the sale of any by-products obtained in any process of distillation.

While on the subject of coal distillation, I should like to emphasize the reference that Mr. Woodhouse made to this matter—that the selling price of these products depends on world-wide competition with products obtained from sources other than coal. It also depends on the demand for these products in the available markets.

It is well known that the gas industry at the present time is suffering very severely from its inability to dispose of the by-products at a remunerative figure, with the result that it has not recently been possible to lower the price of gas in accordance with expectations; it has even been necessary in some cases to increase the price of gas to meet this difficulty. It is therefore very desirable to realize that if processes of this kind are adopted, a serious commercial risk is run which may have an adverse effect on the selling price of electricity.

Our ideas as to the best method of using fuel to produce steam are constantly changing. New processes, such as the use of pulverized fuel, are being developed to obtain more perfect combustion and higher furnace temperatures, and boiler-house efficiencies of 90 per cent can now be obtained, compared with 80 per cent a few years ago.

The difficulty of obtaining, for lining the furnaces, a refractory material that will stand up to these high temperatures without undue maintenance cost has now been solved, by screening the furnace walls with water tubes which are coupled up to and form part of the boiler itself. The circulating system through these tubes is kept distinct from the main circulation through the boiler, and very high rates of evaporation—in some cases as much as 50 lb. per square foot of heating surface—are obtained from these tubes, apparently without any consequent disadvantages.

There are five great advantages in the use of pulverized fuel as compared with boiler-house practice up to the present. These are :—

(1) Greater efficiency in operation, to which I have referred above.

(2) Greater capacity of individual boiler units—it being possible to install boilers each having a capacity of 300 000 lb. of steam per hour, with single combustion chambers. One such boiler would be capable of running a 25 000-kW turbine, and this would realize the dreams of some engineers who advocate the advisability of such an arrangement. I consider, however, that the steam-generating plant in a station should be pooled in order to obtain maximum reliability in operation, and this would necessitate the use of boiler units of somewhat smaller size.

It would not, in my opinion, be advisable to equip such large boilers with mechanical stokers. Several stokers would be required for each boiler, and the proper regulation of the fires would become a difficult matter; in addition to which the breakdown of any one stoker would have the effect of shutting down the whole boiler unit.

This brings me to—

(3) Greater reliability of the pulverized-fuel furnace—there being no moving parts to get out of order and to cause stoppages, whilst the regulation of the temperature in the furnace can be controlled with wonderful accuracy and consistency.

(4) The reduction in the cost of labour in operating such boilers is nothing less than extraordinary. Automatic control can be fitted, and although this is costly it is justified in connection with such large boiler units. Even where this is not fitted, one attendant can control the operation of a battery of boilers having a combined capacity of 1 million lb. of steam per hour.

(5) The efficient use of all classes of fuel is rendered possible. This is an advance on stoker performance, as the same grate area and air supply are not suitable for both rich and poor fuels when burnt on mechanical stokers, whilst it is a simple matter in a pulverized-fuel furnace to adjust the supply of air to suit the class of fuel that is burnt. In addition to this, it is possible to use efficiently the poorest classes of fuel, which have hitherto been looked upon as refuse and cannot be burnt at all on mechanical stokers.

Such a development will be of national importance, as it will make available for service the refuse heaps of old colliery workings which have been accumulating for many years.

When one compares these advantages with what we have been used to in boiler-house practice in the past, I think it is evident that considerable economy, both in capital cost and in operation, can be looked for in the future.

We are now told that the pulverization of fuel has to be combined with low-temperature carbonization of the coal in order to obtain a still further reduction in the cost of production. Any process of this kind must, as I have explained above, be dependent upon the market obtainable for the by-products. On the face of it, however, the proposal sounds more attractive than the ordinary low-temperature carbonization process, as the resultant fuel is obtained in a pulverized form and can be sent direct to the boiler furnaces. This eliminates the necessity for pulverizing the coke or semi-coke that is produced in the ordinary process, with the consequent heavy cost of upkeep of the pulverizing machinery when this material is passed through it.

The process, however, has yet to be demonstrated and proved before it can be accepted for general use.

Load Factor.

All supply engineers are fully aware of the extreme importance of obtaining a good load factor in order to cheapen the cost of production. Unfortunately, statistics show that in this country the load factor obtained in the majority of the undertakings is between 15 and 30 per cent. Those undertakings which are the fortunate possessors of a higher load factor have the benefit of long-hour demand, such as is created by railway traction, colliery pumping and similar loads. It is unfortunate, however, that loads of this nature are only available at present in certain districts.

Experience on the big systems in America also goes to show that a load factor of 45 to 50 per cent can be obtained where these long-hour loads are available.

The statistics issued by the Electricity Commission show that only six undertakings out of 470 in this country obtain a load factor exceeding 45 per cent, whilst the conclusion may be drawn that the combined load factor for the whole generating plant of undertakings in Great Britain was of the order of 28 per cent in 1922–23. There has, of course, been a big drop since the war in the load factor obtainable.

The Birmingham Corporation undertaking is typical of the supplies given in large industrial areas without the benefit of railway or colliery loads, and the load factor on its generating plant, based on units generated, has varied as follows:—

	Per cent
1916	37·0
1917	39·1
1918	38·7
1919	35·7
1920	27·8
1921	27·8
1922	25·0
1923	25·3
1924	26·2
1925	26·0

The reduction in load factor that has occurred during recent years has been due to three causes:—

(1) The bad condition of most manufacturing industries.
(2) The reduction in working hours.
(3) The phenomenal increase in the lighting connections in residential districts.

I should say that the reduction in working hours in factories has had the greatest effect in reducing the load factor, and if this is felt so severely on the capital charges of the supply undertakings, how much more must it be felt on the capital outlay of factories. One can only hope that, when trade does revive, it will be possible to run two or three shifts of men in the factories and so improve the serious position in which we are all placed at present.

Experience shows that the load factor of a residential lighting supply is approximately 10 per cent. It is obvious, therefore, that if this supply is increased to a relatively much greater extent than the power supply, it will have the effect of reducing the average load factor on the system and, in consequence, of increasing the cost of production.

It is therefore incumbent upon supply engineers to do their utmost to foster the use of electricity for cooking and heating, as in this way only can the residential load factor be improved.

The most telling way of developing the cooking and heating load is to arrange an attractive tariff, and the one that seems to find most favour with the average householder is that termed the "contract rate of charge" under which the consumer pays per quarter a fixed sum, generally based upon the rateable value of his house, and a low rate of charge per unit for every unit used in the house—whether for lighting, cooking or heating—the only proviso being that the house must be wired for all three services and a reasonable use made of them.

I believe it is true that the high load factor obtained in some of the large undertakings in this country is largely contributed to by the fact that their residential supply is practically negligible in amount compared with the industrial supply.

The suggestion that has been made in certain quarters, that the general load factor throughout the country can be improved by linking up all the big centres of supply and by taking advantage of the better diversity factor so created, is in my opinion outside the realms of possibility.

This proposal has been tried to a certain extent in America, and experience has shown that the peak load rose as fast as, or even faster than, the output. The expansion of these large systems by means of heavy trunk lines running long distances has not had the effect of improving the load factor on the system, but, on the contrary, it is tending to decrease this as the area of supply grows larger.

In this country there is no evidence that the habits of the population vary as between one large industrial centre and another. The hours of work in the factories are approximately the same, and there is no reason for believing that the peak load in one district would occur at a substantially different time from that in another.

It does not therefore appear, from the point of view of improving the load factor, that there is any justification for incurring the enormous expenditure that would be necessary to link up all the big centres in the country with trunk mains of sufficient capacity to enable their effect to be felt in the operation of the generating stations.

Standardization of Frequency.

To discuss this proposal is rather like trying to play *Hamlet* without the Prince of Denmark, because the long-looked-for Report of the Committee set up by His Majesty's Government is not yet available. From articles that have appeared in the Press it is, however, fairly clear what the proposal is in principle, i.e. to change over to 50 periods those districts in the country that are at present being supplied with alternating current of periodicities other than 50.

Let us try to imagine what is the reason or justification for doing this, and make a rough estimate of the cost.

Again we have nothing definite to go on, as the Report is not available: however, from articles that have appeared it is possible to form some idea that the proposal is designed :—

(1) To make it possible to exchange current between districts by means of large-capacity trunk lines linking them together ; and in this way generally to increase the reliability of the supply, and at the same time obtain greater economy in operation by concentrating the demand on a few of the most economical stations at times of light load.

(2) To reduce the range of apparatus that now has to be manufactured and stocked, and so cheapen the purchase price of all electrical apparatus.

(3) To do away with the necessity of converting alternating current to direct current for general distribution and so take advantage of the cheaper method of four-wire alternating-current distribution.

Considering (1) first, trunk lines for this purpose would require to have a capacity of at least 20 000 kW, and run at a voltage not less than 110 000 between phases. The length of the lines required to connect up all large centres of supply would be roughly 1 900 miles, and the cost would amount to approximately £5 700 000.

It is obvious that the bulk of the supply in each district must be derived from stations on the spot, as the loss in transmission over 50 or 100 miles would cancel out any problematical saving that might be effected through better natural facilities. Such stations having high economy of operation can be designed, and in fact are coming into existence, and it is becoming apparent that each district can economically serve itself and provide its own stand-by plant without any necessity for drawing supplies from other districts at such an enormous capital cost.

By all means link up the individual stations in each district, at a fraction of the cost of linking up nationally, and take advantage of the high economy of operation of the best station in each district at times of light load.

It has been stated that such trunk lines will open up the rural districts throughout the country. It is, I think, obvious that such large-capacity lines cannot be safely tapped except at well-defined centres, and that the opening up of rural districts must depend upon a network of thin overhead lines radiating from the large centres of supply. The rural demand can never justify a heavy expenditure on distribution, and the greatest care and economy will have to be used in designing such distributing systems.

Turning now to (2), there should be an average saving of 15 per cent in the cost of 50-period electrical apparatus, such as generators, motors and transformers, over 25-period apparatus. This is to some extent counteracted by the higher speed at which 50-period motors run, necessitating speed-reduction gear. 50-period induction motors also create a lower power factor on the system, the difference being about 5 per cent, and this curtails the carrying capacity of the distributing mains and necessitates the installation of larger transformers.

There does not therefore appear to be much real advantage in this claim.

As regards (3), it is admitted that there is a very slight flicker noticeable on the lights when supplied with low-tension 25-period current. This can, however, be largely eliminated by suitable shading in living rooms, and it is only in these that there can be any reasonable objection raised. In factories and business premises, and even in drawing offices, it is being very largely used without any inconvenience.

In most large towns direct-current distribution is already in existence, and the recent development of the mercury-arc rectifier, whilst being admittedly rather

more expensive that a.c. transformer distribution, has solved the problem of the high cost of rotary-converter substations and the necessity of employing labour to run them for supplying outlying residential districts.

It must be admitted that direct current is safer than alternating current for domestic apparatus, and now that this apparatus is coming into such general use this point should receive careful consideration.

If railway electrification becomes general in this country—and there is strong evidence that this is coming in the near future—it seems certain that direct current at a pressure of 1 500 volts will become standard. This is being largely adopted on the Continent, and military considerations will probably weigh heavily in the matter. If so, rotary converters or mercury-arc rectifiers will probably be used, and for these 25-period current is far preferable to 50-period. We must not forget that we want the railway load to improve the load factor and reduce the cost of supply.

I have so far dealt with the suggested reasons for such a change. Let us now consider the probable cost.

It would be necessary to replace the whole of the electrical generators, transformers, rotary converters, motor-generators, motors and other a.c. apparatus with new 50-period plant. This would apply not only to the plant belonging to the supply undertakings, but also to that installed on consumers' premises.

It is estimated that about 25 per cent of the electrical plant installed in the country is other than 50-period plant.

I have made a close estimate of the capacity of the a.c. plant that would have to be replaced in the Birmingham area. This amounts to 486 870 kW belonging to the Birmingham undertaking, and 337 350 kW belonging to its consumers.

Total .. .. .. 824 220 kW

	£
The cost of this at £3 10s. per kW would be	2 880 000
Allowing scrap value for the old plant of 6¼ per cent, because there would be no market for it, would realize	180 000
The net cost of replacement would therefore be	2 700 000
There would be other costs, such as the provision of duplicate mains and switchgear to make the change-over possible, the salaries of a considerable staff, compensation for interference with consumers' business, etc., which I have estimated at ..	4 000 000
The total estimated cost for Birmingham would therefore be	6 700 000
Applying this estimate to the rest of the areas in the country using periodicities other than 50, we get a figure for the country of approximately	27 000 000

Can such a colossal expenditure be justified, for the reasons I have indicated above, reasons which, as I have shown, will not really bear investigation ?

If the Government want to develop the electrical industry and to cheapen the cost of supply, it would be far more profitable to spend the money on improving the load factors throughout the country. This could be done by electrifying the railways and equipping the coal mines with complete electrical plant for getting the coal and pumping and ventilating the mines.

Expenditure of this kind would prove to be remunerative, and could be regarded as a compulsory loan to cheapen and foster what are, after all, public utility services.

One word in conclusion on this subject. The United States of America are frequently held up as an example to be followed as regards the wonderful development of their electric supply undertakings, the large number of units they supply per head of population, and so on. I quite agree that they are long-headed, far-seeing business men, keen on efficiency and with a well-known desire for standardization where it will pay. But they run two frequencies in America—25 periods and 60 periods—and they are not contemplating changing over one of these to the other, as far as I have heard. Let us therefore take a leaf out of their book and leave well alone.

Distribution.

A year ago Mr. Woodhouse called attention to the growing cost of distribution, and to the effect that this is having on the cost to the consumer.

It may be of interest to call attention to a development that has recently been introduced in Birmingham, which has had the effect of relieving the ordinary direct-current three-wire network and its system of feeders. I refer to the arrangement that is now made to couple small power consumers to the extra-high-tension three-phase system. Hitherto this system, which is supplied at a pressure of 5 000 volts between phases, has been confined to consumers who have at least 100 h.p. installed, as each service entailed the use of three oil-switch panels for controlling the incoming and outgoing cables and the supply to the consumer. A special type of service connection has now been developed at a very much reduced cost, which makes it possible to supply power consumers whose demand is only 30 h.p. and upwards, the only difference between this and the larger consumer being that the connection is teed off the main instead of being looped in and out, so that there is no alternative source of supply. This is, however, only comparable with the ordinary power consumer off the d.c. network. It is found that this arrangement is likely to have a very beneficial effect upon the cost of distribution generally.

Training of Engineers for Supply Undertakings.

I am frequently asked by anxious parents whose boys are leaving school and propose to take up electrical engineering, what kind of training I should recommend to fit them for the profession, and I expect that the same requests are made to brother engineers in the industry. It may therefore be helpful if I outline my views on this matter.

As a broad principle, I think that a boy should enter a technical college when he leaves school. He is used to class work and to school discipline, and he can follow on along the same lines more easily than he could come back to class work after receiving practical training.

He should spend not less than three years at college, and while there he should endeavour to obtain the degree of Bachelor of Science, or some Engineering degree equivalent to it.

The necessity for demonstrating that he has a good general education as well as a thorough technical education is very important, as he will find that after he has passed through the junior stages of his career, which of course chiefly require technical knowledge, he will have to undertake duties of a managerial nature, which require a more general knowledge and the power to conduct correspondence with lucidity. This can only come easily to a man who has had a good general education, who is conversant with literature, and who is able to convey his ideas with conciseness.

After finishing his technical course at college, he should then spend at least two years in practical work in some large engineering manufacturing works. In some colleges arrangements are made for this practical training to commence during the last year of the technical training, and if this is done it is possible to shorten somewhat the total period.

The works chosen should cover the manufacture of steam-generating plant as well as electrical generating plant, and some drawing-office experience should also be included.

When this training is completed, the boy should be about 21 years of age, and he should be capable of taking a position as junior engineer in any electric supply undertaking. His advancement from this position to higher positions must, of course, depend largely upon his own ability and the impression that he makes upon those in control of the undertaking. Opportunity, however, generally plays a considerable part in his advancement. If a junior does not receive any advancement within a period of five years, it may be taken to indicate that he is not likely to progress in that undertaking, and it would be advisable for him to try to move to some other undertaking. A change of this kind will probably be beneficial to him, in that it will broaden his experience and give him better opportunities for advancement.

It is interesting to note that the Electrical Power Engineers' Association are arranging for those of their members who have passed a certain standard to be allowed to call themselves "Qualified Electrical Engineers." Before they become so qualified, they must have had a certain number of years' experience in supply undertakings of a certain size, and they must have passed the Examination required for Associate Membership of this Institution or some examination equivalent to it. I think that this is a very valuable step in the right direction, in that it will tend to ensure that engineers of supply undertakings can demonstrate that they have been properly trained.

I may say that in my own undertaking in Birmingham it has been the rule now for some years that engineers who have not passed the A.M.I.E.E. Examination or its equivalent cannot rise higher in the technical staff than a certain grade, and those men who do not so fit themselves will find in a few years that younger men will be passing over their heads. I know that it is a hard task for a man who is approaching, say, 40 years of age to turn back and take up subjects that he has not perhaps touched for many years. In the case of old servants, however, a certain amount of latitude should be allowed as long as there is proper willingness and endeavour on the part of the individual to fall in with this very necessary requirement.

I should like to take this opportunity of urging those controlling not only electric supply undertakings but also manufacturing concerns to consider very carefully whether it would not be to the ultimate benefit, both of their own undertakings and of the industry as a whole, to make it compulsory that men on the technical staff have passed a certain standard. The necessity for this is clearly demonstrated by the fact that when one advertises for a technical assistant, out of the 150 to 200 applications that are received only about 20 per cent are of any real use. The rest, whilst they have had some experience, are generally either limited in such a way that they can be trusted to handle only one particular section of the work, or they are obviously unfitted for even as much as that.

If all employers had required a certain standard, men of this kind would never have got as far as they have, and the material available to be drawn upon, while being less in quantity, would be greatly improved in quality.

I am convinced that, by the methods I have outlined, the profession will be able to obtain and maintain a supply of properly trained engineers who can, when the time comes, take up and properly fill those higher positions that will become available as the older men drop out.

Conclusion.

In conclusion, from what I have said there appear to be two main points to which supply engineers should give special attention. It is apparent that great improvements have been and are being made in practically all other directions but these two. I refer to improving the load factors of our undertakings, which have to all intents and purposes stood still for so long, and to decreasing the cost of distribution, which has recently tended to increase and to counteract the economies that are being practised in other directions.

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By J. WILLIAM BURR, Member.

(*Address delivered at* SWANSEA, *5th October*, 1925.)

I was recently reading, with great interest, a return of engineering and financial statistics relating to authorized electricity undertakings in Great Britain, compiled by the Electricity Commissioners. It is a most interesting and valuable compilation of returns submitted by all the authorized undertakers in the country. In their general view of these statistics the Commissioners point out many matters which should have the serious consideration of all engineers in charge of electricity supply undertakings.

I propose to take as the subject of my address one of the sub-headings in this review, namely,

THE CONSUMPTION OF ELECTRICITY IN RELATION TO POPULATION.

We are told that in 1922–1923 some 80 per cent of the undertakings had not reached a stage of development corresponding to a sale of 100 units per annum per head of population, and that sales of 300 units, or over, per annum per head of population had been attained in a few cases only.

The Commissioners also state that on the basis of the census of 1921 the aggregate population of the areas of supply of the local authority undertakings included in the return was approximately 22·8 millions, thus denoting an average sale in 1922–1923 of about 98 units per head of population in such areas. The corresponding average figure for the supply companies' areas is not given, owing to the incompleteness of the figures for the population. I think we may assume, however, with some degree of accuracy, that it does not differ from the above figure to any appreciable extent.

Compare these figures with those given by Continental engineers at the World Power Conference held at Wembley last year.

In Norway, for example, it was stated that the estimated annual consumption per head of population was 2 000 units, or 20 times the annual consumption per head of population in this country. I am quite aware that these figures apply to hydro-electric stations; all the same I see no reason why the difference should be so great. I want to discuss this point to-night and I want to discuss it from a manager's point of view rather than from that of an engineer's. The two aspects are not always the same, as we shall probably see later.

From the figures given it would appear that we have undoubtedly barely touched the fringe of the domestic load in this country, and it is certainly up to us engineers to discover the reason.

(1) Do we grasp the consumers' conditions and requirements?
(2) Is electricity available to all who require it?
(3) Have we a suitable domestic rate of charging for electricity?

Taking the first of these, do we realize that domestic consumers can easily become the greatest and most important of all users? When we do so, we shall, I have no doubt, pay them more attention in the future than we have done in the past. Most of us pay much more attention to power consumers than to domestic consumers. I am beginning to think, however, that our future demands will come from the use of domestic appliances and, after all, the business risk is certainly not so great with the domestic consumer.

We should therefore study their requirements, and should lose no time about it. We must be prepared to give the consumers what they want and not what we think they ought to have. If we think the public are wrong in their demands, it will be necessary to educate them in order to convince them that it is to their advantage to buy and use any particular piece of electrical apparatus. Educational publicity is in my opinion necessary, together with enthusiasm. We must be enthusiastic and, after all, we have reason to be. We must of course temper our enthusiasm by scientific knowledge. We must know what we are talking about. It is not the slightest use to try to mislead the public; that does more harm than good. We must find out our consumers' requirements and then put forward something which we honestly think will satisfy them.

Let me now deal with the next point: "Is electricity available to all who require it?" The answer is decidedly in the negative.

Many people in this town could not at present have a supply of electricity, whatever their wishes might be, and this remark I have no doubt applies equally to other towns, and particularly to rural districts. Why is this? Simply because the cost of running mains or transmission lines is so high that the annual return on the capital involved would not justify the expenditure in these particular districts.

Is there a way out of this? I propose to divide the prospective consumers in question into two classes: (1) Those living in the towns; and (2) those living in rural districts.

Electricity could be made available for practically all townspeople if the Unemployment Grants Committee would allow a grant in aid of the work of mains-laying, which could be carried out principally by unemployed labour.

In regard to the supply in rural districts, it is a question as to whether, even with a grant in-aid from the Government Department mentioned, it would still be a paying proposition.

It therefore means that if a supply is to be available in these districts the Government should be asked to increase the grant, or the cost of the work must somehow be reduced. I admit that the latter can only be done by co-operation with the cable, transformer and switch manufacturers. We want good and cheap cables suitable for operating at high pressure; we want cheap and reliable transformers suitable for mounting at the top of the posts carrying the line; and we want simple, cheap and reliable outdoor switchgear.

I believe that great reductions in prices can be made if the manufacturers will only take the matter in hand. Further, I would point out to manufacturers that this is a problem for them to solve and not for the supply undertaking, as the cost of generation does not enter into the matter to any great extent.

I often wonder whether or not it will be possible in the near future to transmit power cheaply without the aid of wires. I know that I shall be accused of talking nonsense, but all the same the matter has been in my thoughts for a long time, and it must be understood that I am referring to the transmission of only small amounts of power, suitable no doubt for rural districts.

In my student days I was deeply impressed by an experiment carried out by the late Dr. Silvanus Thompson, which consisted of an alternating-current electromagnet placed near a vessel of water in which floated a closed coil of wire, to which was connected a small electric lamp. I remember that the magnet was a perceptible distance away when the lamp lighted, and although I think I know some, if not all, of the difficulties in the way, I have often wondered whether or not this experiment could be extended.

In regard to legislation, I am decidedly of the opinion that the Electricity Supply Acts restrict real expansion, and that attempts should be made to remove many of the restrictions which not only hamper the industry but are, in my view, unnecessary.

I now propose to deal with the third point: "Have we a suitable domestic rate of charging for electricity?" In other words, have we a suitable tariff for domestic apparatus and, if not, is it possible to obtain one?

While I consider that the present tariffs in this country justify the use of electricity for lighting, cooking, intermittent heating and small power-consuming devices, I do not consider that they justify, except in special circumstances, the use of electricity for all domestic purposes.

Generally speaking, tariffs can be grouped under two heads: the "flat rate" system and the "two part" system of charging. In the former, one flat rate is fixed for lighting and another for other purposes. In the latter, that is the "two part" system, a primary or annual charge per kilowatt is made to cover the standing charges, and a secondary charge or small charge per unit is made for current consumed.

The idea of the "two part" system of charging is to encourage consumers to use electricity for purposes other than lighting, as the actual charge per unit is small and the more units they use the lower is the average price per unit paid.

In view of the Commissioners' remarks it would appear that there is in this country at present no tariff which would induce the domestic consumer to use electricity for all purposes, and it may of course be partly due to the cost of the apparatus.

Let us see whether there is any likelihood of the tariffs being reduced in the near future. I propose to take first the cost of generation. Is it possible to reduce this? At the present time electricity is being generated in power stations many of which are fairly old, and although they may have modern plant installed it may be that much of the obsolete plant has not been paid off. In other words, the total cost per kilowatt of available plant is considerably higher than it would be with a new station.

As our generating costs are made up of the two factors, (1) annual charges on capital expended, and (2) running costs, it necessarily follows that this fact will increase the total cost of generation. The outstanding debt on the old plant would disappear in the course of time. The question is, however, should the existing stations be allowed to extend in order to meet increased demands, or should suitable stations be erected at various parts of the country to supply this load and eventually take over the load from the existing stations?

I suggest that as soon as a new station could show a saving on the cost of supply to the consumer equal to the annual capital charges on the old station, the latter should be shut down forthwith, as by that time it has outlived its usefulness. I also think that no interest, municipal or company, should be allowed to stand in the way of this being done. In my view the Electricity Commissioners should have compulsory power in this respect, and their decision should be absolutely final.

One effect of this would be that the generation engineers of the existing stations would do their best to keep their production costs as low as possible, which is all to the public good.

When I referred to the erection of new stations I was not talking of super-stations but of medium-sized generating stations with modern plant and situated about 20 or 30 miles apart, the exact distance depending upon the electrical density of the area. These stations should be suitably interconnected, provided the generating stations are not too far apart, as not only would the expenditure on generating plant be reduced thereby but it would also improve the load factor and reduce the operating costs. It would further secure, to a great extent, continuity of supply.

Speaking generally, the economic result of any particular case could be studied before the interlinking mains were run.

In regard to the much-talked-of super-power station and its possibilities of reducing the costs of generation, I have always held the view that while the thermal efficiency of a medium-sized station, i.e. one with a plant capacity between 25 000 and 50 000 kW, might

be less than the thermal efficiency of a modern super-power station equipped with all the heat-saving appliances, it may easily be that the actual cost per unit sold will be actually higher with the more efficient plant.

The annual charges on the additional capital required to purchase the special heat-saving apparatus may absorb the value of the saving in fuel effected by the use of the plant. It may also be that the larger station has to distribute electricity over a wider area and, as a result, will have to bear higher capital charges for main transmission lines and also higher I^2R losses. It is possible for these conditions to neutralize the difference in thermal efficiency between the two stations.

When I make this statement I am assuming that the super-power station is striving for the highest thermal efficiency, and that its plant would probably consist of boilers suitable for a working pressure of between 350 and 500 lb. per square inch and a total steam temperature between 700° and 750° F., of air heaters instead of water economizers, and of water heaters for raising the temperature of the condensate on its way to the boilers, fed with exhaust steam and steam bled from the turbine at various stages.

The turbine units would, I have no doubt, have as large a capacity as possible and run at the highest speed to conserve space. The steam between the high and intermediate turbine stage would probably pass through a reheater. The exhaust pressure of the steam would naturally be kept as low as possible.

With all the heat-saving apparatus and the best modern plant it is not possible for any super-station to obtain an operating thermal efficiency of more than 25 per cent. It will be noticed that I use the word "operating" thermal efficiency, as the thermal efficiency of any plant obtained on test does not interest me.

Briefly, then, I consider a medium-sized station, well equipped with modern plant of the ordinary type, and well situated in regard to the electrical centre of gravity and the supplies of coal and water, can supply consumers as cheaply as any super-station distributing over wide areas. I would also say that in my opinion the storage of large quantities of coal, the removal of ashes, and the provision of a plentiful supply of cooling water are problems it is often difficult to solve.

In regard to generating stations generally, it is interesting to note that the maximum thermal efficiency of the most recent station was slightly under 20 per cent.

In view of the low thermal efficiency of our generating stations it may be that attempts will be made to discover a cheaper method of generating electricity. It may be that the electrically-constituted atom will be made to give up the enormous energy which it is said to possess. This may or may not be possible; time alone will tell. I do think, however, that there are great possibilities in other directions; for instance, in the carbonization of coal. It may yet be a commercial proposition for the coal to be carbonized at the power station and the liquid products and smokeless fuel marketed.

I now propose to consider the distribution costs. Is it possible to reduce these? I think so. The present costly method of laying cables is wrong. We dig up the roadway, and often the cost of reinstating it exceeds the cost of the cable. Cannot some method be devised for putting cable underground without disturbing the surface of the roadway? Thrust boring has been tried with a small measure of success. The present boring plant, however, is not suitable for all subsoils, and reliable information in regard to the nature of the subsoil and obstructions is not always obtainable. The idea, however, is good and needs developing. Co-operation is required between the Post Office and the electrical, water and gas departments so that in the event of one department opening up, the others could take advantage of the excavation if required. When a roadway is made up or relaid it will probably pay to lay ducts on both sides of it, even if the prospective demand in the district does not justify the laying of a main at that particular time. Every effort should be made to reduce the annual capital charges on the distribution system (not by "skimping" the copper, which may be false economy, but by reducing as much as possible the cost of laying). The running costs should also be reduced to a minimum.

As much attention should be paid to the possibility of reducing the distribution costs as to the generation costs. Let us assume that our generation and distribution costs are reduced to an absolute minimum—and I should like to say here that in my view this does not always depend upon the plant but often upon the operation of the same. That is where an engineer who is also a manager comes in. The manager not only studies engineering and aims at obtaining the highest possible efficiency for his station, but also studies all factors which contribute to a reduction in the working costs by careful administration and by educating all the employees. An employee interested in his work is worth two who watch the clock. The manager should know a little of psychology—many do by intuition. He must put the right men in the right place and aim for team work.

I think that it is not generally realized what difference it makes in the works costs if the staff and men all work together instead of against each other. Whilst I have no wish to favour the workmen unduly, I would say that if more time were spent in trying to get the employees interested in their work and to pull together than in reducing wages, I think it would be better for the undertaking generally. Low wages do not, in my view, necessarily mean low costs.

Having produced our units at the lowest possible cost, we must see that they are sold at a price which will give a reasonable return on the capital expenditure involved.

In municipal electricity undertakings the income need not be more than is required to cover all costs, including the capital charges and an adequate sum to be placed to reserve. If the capital necessary for municipal undertakings were secured by the Government there would be no excuse for allocating profits to the relief of the rates. Any profit should, I consider, be returned to the consumer by reducing the price of electricity. In the event of a loss, this would of

course have to be met by an increase in the price of electricity per unit.

I am afraid, however, that I am getting off the track. The point now is: Having produced electricity at the lowest possible cost, can we frame a tariff which would be acceptable to domestic consumers for all purposes? Can we frame a tariff similar in any way to the tariff which attracts consumers on the Continent and makes them use practically 20 times the amount of electricity that we do in this country?

The usual tariff on the Continent is, I believe, an "all-in" one; that is, one in which the same charge is made for electricity irrespective to the use made of it. It is so much per kilowatt-year. If, therefore, anyone pays for one kilowatt-year he may consume 8 760 units if he likes and he may use them for any purpose he desires. For example, if the charge were £10 per kilowatt-year, a consumer could use 8 760 units, for which he would pay an average price of approximately a farthing. My information, however, indicates that the diversity factor is usually 2, so that the actual cost per unit would be a halfpenny.

Somebody will no doubt point out that the charge is only obtainable in districts supplied with electricity from hydro-electric stations and that it is easy to understand why this method of charging is adopted, as the capital charges in this type of station practically constitute the total costs of production, so that within the capacity of the station the output of units effects very little the running costs.

I agree, but in view of the much higher capital charges incurred with hydro-electric stations than with steam-driven stations, and of the fact that the only seriously increased cost in the steam station with an improved load factor is the coal, I often wonder whether or not an "all-in" charge could not be made in this country. I am inclined to think that it could, under certain conditions, and I feel, rightly or wrongly, that a reasonable "all-in" charge for electricity for all domestic purposes is a big step towards the realization of our slogan "Electricity for Everybody and for All Purposes." The simplicity of the charge and the simplicity of the wiring would, I am sure, appeal to the consumer, and the exit of the integrating meter and the fact that he would not be called upon to explain the maximum-demand system to the consumer would, I am sure, appeal to the engineer.

I am assuming then, rightly or wrongly, that our problem of domestic electrification is made much simpler if we have a suitable "all-in" tariff for this purpose.

In order to solve our problem completely we must deal with two further points. The first is the wiring of premises, and the second is the equipping of the same with electrical apparatus for all domestic purposes.

I estimate the cost of suitably wiring and fully equipping a villa residence of, say, seven rooms to be £115. I include for a liberal amount of copper in the wiring and for the installation of 3 fires, 1 cooker, 1 vacuum cleaner, 1 clothes washer, 1 ironer, 1 heating element for hot-water tank, 1 small motor for cleaning knives and boots, and various pieces of small apparatus such as quick-boiling kettle, toaster, etc.

I think that the majority of people would not be prepared to pay the sum mentioned, although it would undoubtedly be saved in a very short time. We must therefore look to the manufacturers for their co-operation in this matter, with a view to a reduction in the price of the various apparatus, particularly the cooker, clothes washer and ironer. I believe that by mass production they could reduce prices enormously.

If the undertakers are prepared to take a risk by offering a suitable low "all-in" tariff to all consumers proposing to use electricity for all purposes, I think that the manufacturers should also be prepared to take a risk by producing electrical apparatus in mass at a low price and to chance the market.

The undertakers would also have to be prepared to wire premises and supply apparatus on easy terms. It may be that the manufacturers would co-operate in this way also.

I feel sure that this, in itself, would give a great fillip to the electrical industry.

Let me briefly summarize my remarks.

In order to increase the use of electricity for domestic purposes in this country we must eliminate all waste, both in time and in material, inside and outside our generating stations, and deliver electricity to the consumer at the lowest possible cost.

If we could obtain a supply of electricity in bulk from another source at a cheaper rate than our cost of generation, after taking into consideration the annual charges on any displaced plant, we must do so in the public interest and, incidentally, in the interest of the electrical industry. The Electricity Commissioners should have compulsory powers in this matter.

As far as possible the supply should be available to all who require it.

We should formulate a tariff which will encourage the increased use of electricity for all purposes by all sections of the community.

The tariff should be easily understood by the consumer and, if possible, be an "all-in" charge per kilowatt-year, so that integrating meters could be dispensed with.

A hire, or hire-purchase, scheme for installation work and electrical apparatus should also be instituted.

Manufacturers of electrical apparatus should supply apparatus and replace parts at the lowest possible price, and the undertakers should be prepared to maintain the apparatus at actual cost.

We must educate the public to use electricity in their houses for all domestic purposes. It is not sufficient to advertise freely; we must get into direct contact with the consumer.

We must have fully-equipped showrooms and demonstration rooms, and make it worth while for the public to visit them.

We must see that all our consumers are satisfied. A consumer who appreciates the value of the electric service is an excellent canvasser.

In conclusion, I ask the members to consider for a moment what it would mean, both to the electrical supply industry and to the community as a whole, if electricity were used as freely in this country for domestic purposes as it is in many others.

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By F. J. MOFFETT, B.A., Member.

"IMAGINATION IN ENGINEERING."

(ABSTRACT *of Address delivered at* BIRMINGHAM, 21*st October*, 1925.)

Imagination is commonly associated, in the mind of the man in the street, with those possessed of an artistic talent—poets, painters, dramatists and such like. The engineer is not, as a rule, credited to the same extent with this power—at least that is my impression. He is in the minds of the general public the man who depends, for the solution of the problems set before him, partly on the use of mathematics and partly on rules and laws formulated as a result of the experience of generations of engineers. He is considered to be a matter-of-fact, sensible sort of being with whom it is slightly absurd to associate any imaginative characteristics. I fancy that even engineers themselves are to a certain extent guilty of this attitude, and I trust that in the course of my remarks I may do something to modify it.

In the most general acceptation of the term, imagination may be defined to be the power or process of producing mental pictures or ideas. According to John Stuart Mill, "I am said to have imagination when I have a train of ideas, nor is there any train of ideas to which the term 'imagination' may not be applied."

When the train of ideas simply reproduces without any material alteration the image or picture of past experiences or phenomena the process is called "reproductive imagination." When by a process of selective combination of ideas a new picture is produced, we have creative or productive imagination. In the child the imagination is usually purely reproductive: it can only pass into productive imagination after sufficient experience has been gained to create a new mental world.

Tyndall, in his essay on the scientific use of the imagination, says: "Philosophers may be right in affirming that we cannot transcend experience: we can, however, magnify, diminish, qualify and combine experiences so as to render them fit for purposes entirely new. In explaining sensible phenomena we habitually form images of the ultra sensible. There are Tories even in science who regard imagination as a faculty to be feared and avoided rather than employed. They have observed its action in weak vessels and are unduly depressed by its disasters, but they might with equal justice point to exploded boilers as an argument against the use of steam. With accurate experiment and observation to work upon, imagination becomes the architect of physical theory. Scientific men fight shy of the word because of its ultra-scientific connotations, but the fact is that without the exercise of this power, our knowledge of nature would be a mere tabulation of co-existences and sequences."

In the above words Tyndall aptly describes the creative or constructive imagination, which is composed of three factors, the emotional, the intellectual and the unconscious.

The emotional element, or the element of feeling, is the origin of all invention and discovery. There must be some urge to induce action. We all have wants, cravings, unsatisfied impulses. Frequently the need of bread and butter exerts a powerful drive. Many men have the desire to wrest secrets from nature, and others are fired with the ambition to do something to improve the conditions of life for their fellow men.

Creative imagination is accompanied by many emotions—pleasure or pain, hope or depression. Anyone who has made even a minor discovery knows the fine glow of satisfaction which results from it, the joy of success or perhaps the dejection of failure. It is a well-known fact that many inventors, in spite of continual failure to achieve success, refuse to be daunted and persist in their efforts though these are unrewarded.

A classic example of the emotional element is the discovery by Archimedes, the Greek philosopher, of the method of determining the specific gravity of gold. Hiero, King of Syracuse, was anxious to know whether the crown which was supposed to be of gold did not contain some silver. Archimedes puzzled over the problem till one day he was stepping into his bath and observed the water running over. It at once occurred to him that he could ascertain whether the volume of the crown was the same as that of an equal weight of gold by putting them separately into a vessel of water and observing the overflow. So overjoyed was he when this thought struck him, that he ran home naked through the streets of Syracuse crying "Eureka, Eureka!"

The intellectual factor involves two processes, dissociation and association.

Dissociation, the preliminary process, takes a train of ideas or concepts which it analyses, sorts out and makes suitable for the formation of new combinations. Association, the final or positive process, chiefly depends on the principle of contiguity and resemblance. The most important element in the intellectual factor is the capacity for thinking by analogy, that is, by partial and often accidental resemblance.

An illustration of the power of thinking by analogy is the discovery of the Gothic style of architecture. We can imagine an architect in the days of King

Stephen setting out to find some improved design for the construction of churches and cathedrals, and being struck by the resemblance of an avenue of trees meeting overhead to a beautiful roof. This, I believe, was the origin of the wonderful Gothic nave in some of our cathedrals.

The unconscious factor is in many ways the most wonderful of the three, as its working appears so mysterious. Very frequently this factor is spoken of as inspiration, which implies that the ideas are supplied by some external power.

We all, I fancy, are in the habit of saying at times when faced by some knotty problem, that it is better to sleep on it. This means nothing but that we are deliberately giving the unconscious element an opportunity to come into action. I am so firm a believer in the value of the unconscious element that I much prefer, when engaged on any specially difficult work, to call a halt for some few days and allow my mind to put in what I may call its automatic work. In this connection change of scene and complete rest greatly assist the process, and I feel sure that most members will agree that holidays are by no means waste of time, even when judged simply by the criterion of achievement.

Ribot, a French philosopher, asked an engineer of his acquaintance to describe how his imagination worked, and this is his description: "The so-called creative imagination surely proceeds in very different ways according to the temperament, aptitudes, etc. We may, however, as regards mechanical inventions, distinguish four sufficiently clear phases—the germ, incubation, flowering and completion.

"By germ I mean the first idea coming to the mind to furnish the solution for a problem that the whole of one's observations, studies and researches has put before one, or that put by another has struck one.

"Then comes incubation, often very long and painful or, again, even unconscious. Instinctively, as well as voluntarily, one brings to the solution of the problem all the materials the eyes and ears can gather.

"When this latent work is sufficiently complete the solution suddenly bursts forth, it may be at the end a voluntary tension of mind or on the occasion of a chance remark. But this image always appears simple and clear.

"In order to get the ideal solution into practice there is required a struggle against matter, and the bringing to an issue is the most thankless part of an inventor's work. In order to give consistency and body to the idea caught sight of, one must have patience and perseverance through all trials. One must view from all sides the mechanical agencies that should serve to set the image together until the latter has attained the simplicity that alone makes invention valuable. Thanks to a profound acquaintance with known mechanical methods, the inventor succeeds through association of ideas in getting novel combinations producing new effects, towards the realization of which his mind has in advance been bent."

The above description indicates clearly the stages on the road to competed achievement of the creative or constructive imagination.

In the realm of scientific discovery Michael Faraday stands out as one of the great figures, and it is very fitting to refer to his methods when addressing a gathering of electrical engineers. It will be seen that imagination played a great part in his achievements.

As many of my audience will remember, Faraday at the age of 13 was apprenticed to a bookbinder in London with whom he served for 8 years. During this time he was greatly interested in science and devoured any scientific books which came into his hands. Amongst the books which he bound were some scientific works, which he took the opportunity to absorb. At the age of 22, to his great joy he was appointed assistant to Sir Humphrey Davy at the Royal Institution, and 18 years later at the age of 40 reached the crowning point of his career, when he made the epoch-making discovery that a conductor when moving through a magnetic field had current generated in it. The 18 years at the Royal Institution had been spent largely in wide reading and in confirming by experiment the phenomena described in the books he read. This was the preparatory period during which the facts and material necessary as a basis for the due operation of his imagination were collected and absorbed. His mode of attacking any problem was intuitive rather than logical, though when on the track of a solution his reasoning, proceeding by the process of elimination, of trial and error, was sound and logical enough. Helmholtz in his Faraday Lecture of 1881 stated: "It is in the highest degree astonishing to see what a large number of general theorems, the methodical deduction of which requires the highest powers of mathematical analysis, he found by a kind of intuition, with the security of instinct without the help of a single mathematical formula. The fundamental conceptions by which Faraday was led to these much-admired discoveries have not received an equal amount of consideration. They were very divergent from the trodden paths of scientific theory and appeared rather startling to his contemporaries. His principle was to express in his new conceptions only facts, with the least possible use of hypothetical substances and forces."

Faraday himself in a note on the margin of one of his papers warned himself to be practical: "I must keep my researches really experimental and not let them deserve anywhere the character of hypothetical imaginations."

Tyndall in his address on "Faraday as a Discoverer" says: "When an experimental result was obtained by Faraday, it was instantly enlarged by his imagination. I am acquainted with no mind whose power and suddenness of expansion at the touch of new physical truth could be ranked with his. Sometimes I have compared the action of his experiments on his mind to that of highly combustible matter thrown into a furnace: every fresh entry of fact was accompanied by the immediate development of light and heat. The light which was intellectual enabled him to see far beyond the boundaries of the fact itself, and the heat which was emotional urged him to the conquest of this newly revealed domain. But though the force of his imagination was enormous, he bridled it like a mighty rider

and never permitted his intellect to be overthrown. In virtue of the expansive power which his vivid imagination conferred upon him, he rose from the smallest beginnings to the grandest end."

Faraday admitted that he was no lover of mathematics, and pleaded almost pathetically in a letter to Clerk Maxwell for some easier mode of expressing scientific ideas. "There is one thing I would be glad to ask you," he wrote: "When a mathematician engaged in investigating physical actions and results has arrived at his own conclusions, may they not be expressed in common language as fully, clearly and definitely as in mathematical formulæ? If so, would it not be a great boon to such as we, to express them so—translating them out of their hieroglyphics, that we also might work upon them by experiment?"

I feel sure that many of the members of this Centre will sympathize with Faraday in his appeal. Surely many of the papers read before this Institution could with advantage leave out the pages of symbols and substitute, as Faraday says, common language.

Tyndall comments on Faraday's lack of mathematical training in the following words: "It is impossible to say how a certain amount of mathematical training would have affected his work. We cannot say what its influence would have been upon that force of inspiration which urged him on: whether it would have daunted him and prevented him from driving his adits into places where no theory pointed to a lode. If so, then we may rejoice that this strong delver at the mine of natural knowledge was left free to wield his mattock in his own way. It must be admitted that Faraday's purely speculative writings often lack that precision which the mathematical habit of thought confers. Still, across them flash gleams of prescient wisdom which will excite admiration through all time: while the facts, relations, principles and laws are sure to form the body of grand theories yet to come."

This anticipation of Tyndall's was amply fulfilled. Clerk Maxwell and Kelvin who followed him worked out fully and completely the theories underlying the discoveries of Faraday.

In his aversion to the use of mathematical methods Faraday is a striking contrast to Newton. Sir Isaac Newton as a boy was extremely interested in mathematical and mechanical problems, and on this account was sent to Trinity College, Cambridge, at the age of 19. Four years later the method of fluxions, as he called it, occurred to him, and during the subsequent three or four years he worked out the theory of the fluxional calculus. At the same time he was experimenting with prisms and lenses and also with chemical apparatus, showing that he had an experimental as well as a mathematical side to his nature.

At the age of 25 he was elected Fellow of his College, and two years later wrote a mathematical paper which resulted in his being appointed Lucasian Professor of Mathematics.

The science of optics now attracted his attention. He invented a reflecting telescope the lenses for which he prepared in his own glass-works, and while experimenting with this discovered that white light was a mixture of differently refrangible rays of various colours.

In his optical work Newton used what may be called the experimental-mathematical method, in which there were three steps. First, determination of the fundamental concepts by experiment from the phenomena. Second, mathematical elaboration of these concepts, usually by the aid of the calculus; and last, the verification of the mathematical deductions, again by experiment. In spite of his great mathematical powers, he was accustomed to confirm his deductions by experiment. His great work in the discovery of the laws of motion and of gravity may, however, be said to be almost entirely the achievement of his wonderful mathematical imagination.

In commerce again there is a great field for the imagination. In fact the stories of the development of some of our great commercial enterprises read like romances. Many instances will no doubt occur to my hearers, but I propose briefly to refer to the career of Henry Ford. He was born on a farm at Dearborn, Michigan, U.S.A., and it was intended that he should follow his father's calling. Apparently from his early years it was borne in upon him that there was too much hard hand-labour on farms. This feeling set in motion his imagination, which led him to suspect that much of the work might somehow be done in a better way. The better way appeared possible through the application of mechanics, for which he had a strong bent. When quite a boy he had a workshop with home-made tools—in fact his toys were all tools.

At the age of 12 occurred a big event—Ford says the biggest event of his early years. While his father and he were driving to town one day, they met a portable engine and boiler used for driving a threshing machine. Ford had previously seen many of such engines drawn by horses, but this was the first he had seen which was self-propelled by means of a chain between the engine and rear wheels of the wagon on which the boiler was mounted. It was this encounter which suggested to him by analogy the possibility of automotive transportation, as he calls it. His first idea was to develop a tractor which would take the place of horses in the hard labour of ploughing and also be suitable for hauling a wagon along a road. He found, however, that people were more interested in something which would travel along the road, and he accordingly devoted his energies to the production of a car. The first he built was a steam car, which was not satisfactory owing to its weight. The idea of an internal-combustion engine was suggested to him by the Otto "Silent" gas engine which was being developed in England, and after being called in to repair one of these engines he built a small model to see that he understood the principle. This model worked well, and in 1890 he commenced a two-cylinder engine. In 1892 he completed his first motor-car, on which the two-cylinder engine was fitted, and this ultimately ran to his satisfaction. This was the first and, for a long time, the only motor-car in Detroit, and Ford was the first licensed chauffeur in America. Encouraged by this success, he determined to devote his energies to the manufacture of motor-cars, and a company was formed to exploit his invention. The methods adopted by the company did not commend themselves

to him. As he himself says in his autobiography, "The most surprising feature of business as it was conducted was the large attention given to finance and the small attention to service. That seemed to me to be reversing the natural process, which is that the money should come as the result of work and not before the work. An article was not built with reference to how greatly it could serve the public, but with reference solely to how much money could be had for it. A dissatisfied customer was regarded, not as a man whose trust had been violated, but either as a nuisance or as a possible source of more money in fixing up the work which ought to have been done correctly in the first place. The automobile business was not on an honest basis, to say nothing of being from a manufacturing point on a scientific basis.

"I determined absolutely that never would I join a company in which finance came before work or in which bankers and financiers had a part. And further, that if there were no way to get started in the kind of business that I thought could be managed in the interest of the public, then I simply would not get started at all. Business as a mere money-making game was not worth giving much thought to and was no place for a man who wanted to accomplish anything. The only foundation of real business is service. A manufacturer is not through with his customer when a sale is completed. He has then only started with his customer. The sale of a machine is only something in the nature of an introduction. If the machine does not give service, it is better for the manufacturer if he never had the introduction, for he will have the worst of advertisements—a dissatisfied customer. It is the function of business to produce for consumption and not for money or speculation. Producing for consumption implies that the quality of the article produced will be high and that the price will be low. The producer depends for his prosperity upon serving the people, and money comes naturally as the result of service."

If time had allowed I might have referred to Ford's general methods, his factory system, his treatment of his workers, his labour-saving devices—but I consider that the greatest discovery Ford has made is the principle of service.

I have referred to Faraday and Newton in scientific discovery, and to Ford in commercial discovery. These are men who stand out above their fellows. We cannot all be Faradays or Fords, but all of us in whatever department of engineering we are engaged require the creative imagination. The layout of a power house and a system of distributive mains, the manufacture of machinery for the generation and transformation of electrical energy, the design of switchgear, the installation of electric power and light, the provision of telegraphic, telephonic, and wireless communication, the development of furnaces and welding appliances—all the wide range of constructive problems which confront the electrical engineer—involve the faculty of discovery and invention in a greater or less degree.

It is often said in a semi-jocular strain, that an engineer when called upon to produce a scheme has only to take from the pigeon-hole the appropriate specification. This statement is wide of the truth. In each new scheme much of the work will proceed on the lines of previous schemes, but there are always new problems which demand the assistance of the imagination for their solution. Seldom, if ever, are the solutions of two apparently similar problems identical, apart from the fact that with the increase in our knowledge new methods of solving any particular problem are continually becoming possible.

Recently I paid a visit to the Belfast and Edinburgh generating stations. Both are of approximately the same size, both are placed on the sea coast, both were erected about the same time, and yet the layouts differ very considerably, showing the drift of different creative imaginations dealing with a problem in which the general governing factors were identical.

The field open to the electrical engineer with creative imagination is enormous. Take the steam-driven generating station. It is well known that the overall efficiency from the heat energy in the fuel to the electric energy at the switchboard is dismally low, not more than, say, 10 per cent in the average station, and 20 per cent in the most recent super-station. Surely there must be some means of reducing this enormous waste of heat energy, from 80 to 90 per cent of the total energy in the fuel. On a small scale much higher overall efficiency has been obtained through the utilization of the waste heat in the exhaust. No remedy, however, is yet forthcoming for the large station.

Take the question of storage. The lead accumulator has held the field almost without threat of competition for the last 30 or 40 years. It is the weak link in any scheme which involves the storage of energy, since it has an extremely low capacity compared with its cost and weight, and its life even when treated with the utmost care is very short. The discovery of a more efficient method of storing electrical energy which would compare favourably with the gasholder would greatly facilitate the generation of power by means of the tides or the wind. Want of a better means of storage of electrical energy is the chief obstacle in the way of deriving vast supplies of power from the energy of the wind.

Take the question of atomic energy. This may be looked upon as a subject which concerns the physicist rather than the electrical engineer, but at any moment it may become of vital importance to the latter. As is well known, some of the most able and acute minds in this and other countries are devoting their energies to this question, and new light is continually being gained through their efforts. Sir William Bragg says: "I am of opinion that atom energy will supply our future need. A thousand years may pass before we can harness the atom or to-morrow might see us with the reins in our hands. That is the peculiarity of physics—research and accidental discovery go hand in hand."

I have suggested one or two fields in electrical engineering where there is unbounded scope for the creative imagination, but I am sure it will be agreed that there is practically no limit to the number of scientific problems awaiting solution.

Imagination is possessed in some degree by all normal persons. I would venture to claim that the average engineering designer's imaginative power is above the common level, but in view of the nature and scope of his work I consider that the development of this faculty has not kept pace with his technical powers.

There is endless scope for the exercise of the imagination by the designer, as practically the whole of his creations are intended for the use of other people. Granted a sufficiently lively imagination, many of the troubles due to inaccessibility, inadequate protection, want of provision for renewal of wearing parts, in fact to failure to realize the point of view of the user, might be largely overcome.

In electrical apparatus in particular there appears to be a boundless field for imagination, especially in connection with appliances in which means have to be devised to circumvent the unconscious human tendency to commit suicide. The designer must in fact bring himself to realize that the desire to gratify the sense of touch has not yet been eliminated, even in the trained electrical attendant. To still greater lengths must the use of the imagination be carried in the design of apparatus for domestic use. The designer must by full use of his imaginative faculty suppress for the time being the instincts of his training, so as to adjust his focus to see, say, a griller switch, through the eye of the average cook.

In no sphere is the need for imaginative enterprise more immediately apparent than in industry, where the search for an explanation of trade depression is engaging so many minds. Lack of imagination in catering for foreign needs and conditions may not be the principal course, but I suggest that it may be a strong contributory factor in the decline of overseas trade: the time has passed when our wares will sell on the strength of their place of origin.

In the conduct of human relationships the necessity for what may be termed the sympathetic imagination is truly enormous. The relations between employers and employed are at the present time in a very strained condition. I suggest that one of the principal obstacles in the way of a solution of many of our difficulties is simply lack of imagination on both sides.

On the present occasion I have only glanced at these questions: to deal with them in detail would require another paper.

What are we doing to encourage the growth of the imagination? The child is father of the man and we needs must start with the child.

Professor Welton in his work on the psychology of education writes as follows: "From the simple contrivances of the child to the invention of the most delicate or the most powerful machinery or of the most elaborate instruments for aiding advance in science, each is the realization in appropriate material of an ideal plan adapted to an ideally conceived end. For such inventions the mind must not only be stored with all pertinent knowledge but must have a particular bent. We all make our little inventions in daily life, but those who first imagine, then produce—it may be in successive stages each more perfect than the last—instruments that change profoundly the condition of men's lives or knowledge, are few. Nowhere can we better learn the lesson that ideals cannot be taught.

"Material and, it may be, inspiration and encouragement may be given, but the inventive mind can only work when free and untrammelled. The course of the school is obvious. In all constructive work it should leave as free a hand as possible in the planning: should welcome originality even if it spoil material: and should give to those who show they can imagine new constructions generous opportunity to carry out their practical ideals."

Sanderson of Oundle made it his life's work to develop a system of education in public schools which would appeal to the constructive and creative instincts of the boy. Many will be familiar with his methods, but for those who are not I will endeavour to give a brief description of them.

The root idea underlying all his work was that science did not hold the position it should in modern education. In teaching, the method of research should be adopted as far as possible: boys and even quite young children should be allowed to discover things for themselves. Whilst holding that language and literature must always form the basis of education, he believed that science properly taught supplied something which could be obtained in no other way.

Sanderson was a great believer in using what he called the romance of science as a stimulus to his boys. Faraday was a great source of inspiration to him—in fact Faraday may be said to have been constituted the patron saint of Oundle School.

Sanderson's methods, as would be expected, aroused great opposition from the traditional type of school, but he steadily proceeded along the path he had chosen, and there is little doubt that he has considerably influenced the methods not only of the public schools of the country but also of the elementary schools.

In my opinion every possible effort should be made in all schools to rouse the interest and enthusiasm of the scholars, in other words to stimulate to the utmost their imagination. In the majority of public schools the zeal for sport of every kind is tremendous. Is it not possible to awaken similar zeal for the pursuit of knowledge?

As a final word I would say that imagination is one of the greatest faculties with which we are endowed. If we give full scope for its exercise and have the courage to follow its lead, we shall have added power to deal not only with the technical problems which confront us as engineers but also with the wider problems of human relationships, to the solution of which engineers can make valuable contributions.

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By R. W. Gregory, Member.

(Abstract *of Address delivered at* Newcastle, *26th October*, 1925.)

I have often felt that an essential part of a Chairman's address should be a plea of justification for the continued existence of the profession to which he belongs.

Engineering is one of the oldest professions. Throughout the ages the principal justification for the existence of the engineer has been that he has made it possible for large numbers of people to live together more or less healthily in towns and cities. By living in cities, by rubbing shoulders with his fellow men, by a mixed process of competition and combination, man has progressed in the arts and become civilized; in fact he has become urbane.

Cities have been a necessity of civilization, not only because of this rubbing of shoulders and crossing of wits, but also because the gregarious habit reduces the cost per head of the necessities and the desirable comforts of life. Owing to this, life can be won more easily in the city, there is more leisure for the practice of the arts and more wealth available for the establishment of schools and universities and for investment in capital works to make life still easier.

Living in cities, however, especially in the industrial cities of this country, does not yet provide the perfect life. We engineers have still a great deal to do towards the improvement of our cities—to being in sunlight and quiet, and pure air and cleanliness.

The present trend of engineering appears to be towards bringing urbanity to rural surroundings, making it possible for the rustic, living in the sweetness of the country, to obtain many of the services which in the past were only obtainable in the smoke-laden air of the city. Electricity is perhaps the brightest of the magic buttons which are being rubbed to attain this end. It is, I think, a safe thing to predict that during the next decade electricity and the automobile will radically alter the life of rural England.

I sometimes wonder whether we English are as enterprising a people as we like to think ourselves to be. When one has travelled abroad, one sometimes returns with the feeling that our old country is not quite as agile as she was in her younger days during the great Victorian period. She appears to be hampered with a load of existing capital works and legal restrictions which, in the electrical industry at least, prevent her from getting on with the business as quickly as she ought to do. In fact, she is really overburdened with her own civilization.

I remember when I returned from a visit to the United States two years ago, full of the tonic effect which is vulgarly called " beans," and which all engineers, but particularly electrical engineers, must experience when visiting that engineer-made country, feeling just a little depressed by this, my home town—with its little, low, smoke-grimed buildings, its antiquated hotels and generally its lack of light and sparkle, both by day and by night; and it was a little galling for me, an engineer, to have my faith in the old country restored, not by the urban enterprises of the district, but by the marvellous organization and wonderful exhibits of the Royal Agricultural Show. I am not using this as an argument for rural electrification or a return to the simple life, but merely to emphasize my point that in matters of engineering enterprise, particularly electrical engineering enterprise, we are tending to follow rather than to lead—although perhaps not so much in design as in application.

We have to keep clearly in mind that electrical development is a world movement. The whole world, civilized and uncivilized, is crying out for electric power. The men in the bush and the backwoods, the inhabitants of the high veldt and the uttermost islands of the Empire, are developing their electric supply systems as fast as or faster than we are, for they all see in electricity the means of obtaining the service they need to increase the output of their industries and to improve their existence. Whatever England does in the practice of electrical development may have little effect on the rest of the world, but a large effect on England herself. The rest of the world is not waiting for England to electrify, and unless she is practised in the art at home she cannot reasonably expect to get her share of the world trade in electrical machinery and appliances, a trade which is bound to grow in volume year by year.

The reluctance of our railways to electrify their main lines may be justified by the economics of the moment, but it is conceivable that the electrification of a British main line would have far-reaching effects on our foreign and colonial trade in railway-electrification material. Moreover, as a training ground for men who could take the home country practice and tradition abroad, it would be invaluable to the Empire.

Again, we have to remember that the engineering of the backwoods is not yet to be learned in England. The essentials of such engineering are high voltages and low capital cost, involving cheap methods of construction and risks balanced against service.

Experience at home in rural distribution and the development of cheap methods of supply would surely have its effect on our export trade; for, when given the chance, British engineering brains are capable of producing an engineering practice which rivals the world.

Rural electrification deserves the study of all supply engineers. The characteristics of rural loads are that they are sparsely distributed and small in quantity. The capital cost per kilowatt connected must therefore be larger than in the towns and industrial areas,

and the essential to the solution of the problem is the reduction of the capital cost, even at the expense of the service given. A 99 per cent service is considerably cheaper to give than a 99·9 per cent service, and the former is all that is necessary, at least during the pioneering period.

During the past summer our city and district were honoured by official visits from the Institution of Mechanical Engineers and the Royal Institute of British Architects. The Mechanical Engineers during their visit paid homage to the memory of that great Tynesider, George Stephenson, when they celebrated the centenary of the first steam railway, the construction of which, to our everlasting honour, was due to the brains and enterprise of North-East England.

The visit of the Royal Institute of British Architects interested electrical engineers in many ways. There are many interests which are common to the two professions, and at the present time the views of the one profession of the work of the other are bound to cause a reaction which will affect the community at large.

At the Conference in Newcastle there were those who expressed sorrow at the manner in which Dobson's classic façades had been treated by the men who worked behind them. Shop fronts had been pierced into them which ignored altogether the architectural form of the buildings of which they were part. Gaunt gilt letters sprawled across the rows of fluted pilasters, and vulgar night-signs were being erected in growing numbers, which showed a lack of reverence for the classic tradition and spoiled the effect the architect had intended his buildings to produce.

It is easy for the student and specialist to follow and to agree with the architect's point of view, but to the man in the street, and particularly to the man who owns a shop, this point of view is obscure. If he could express himself in architectural language he might retort that this apparently sad state of affairs is brought about by an endeavour to force a dead art upon a living people.

Those of us who have seen the effect of flood-lighting on some of the business buildings in other countries, know how electricity and architecture can combine to make advertising beautiful. Even the much-maligned electric night-sign of the pills, whisky and beef-extract order is not without its charm. It is not all ugliness, and in this clouded climate of ours it does add a little sparkle and gaiety to an otherwise drab outlook. I am not alone in thinking this and I would ask you to listen to the words of Mr. G. K. Chesterton * when he was taken on to Broadway by night :—

> "When I looked at the lights of Broadway by night I made to my American friends an innocent remark that seemed for some reason to amuse them. I had looked, not without joy, at that long kaleidoscope of coloured lights arranged in large letters and sprawling trademarks, advertising everything from pork to pianos through the agency of the two most vivid and most mystical gifts of God—colour and fire. I said to them in my simplicity—'What a glorious garden of wonders this would be to anyone who was lucky enough to be unable to read.'"

* G. K. Chesterton: "What I saw in America."

Are we to give up all this joy and wonder because we *are* able to read and would be pleased if pills were prohibited, beef extract banished and whisky winked at ?

The outstanding characteristics of the majority of our industrial towns and cities are their darkness, dinginess and dirtiness.

Our architects give us buildings rivalling the ancient models which inspired them, but under our sunless skies and in our smoke-laden atmosphere they lose much of their charm, even when fresh from the mason's chisel. After a few years they become black, the effects of light and shade disappear and with them much of the impression which the architect intended to obtain. Small wonder, therefore, that the man in the street ceases to respect the architecture of his town and gives that lack-lustre look when talked to by an enthusiast. Dr. Dunn tells us that the annual sootfall on Newcastle is 6 500 tons, and Newcastle is a comparatively clean town. This is the root of the evil.

The art of Greece reared in sunshine was not made to be transplanted into mirk. Venus with a sooty face is a slut, and Eros a street urchin. We may not acquire a Mediterranean sky or a vertical sun, but we surely ought not to defile our atmosphere or to add deliberately to the fogs and mists to which our country is subject.

For the sake of cleanliness and the health and cheerfulness of the community, everything should be done to encourage the use of smokeless heating systems, of which there are so many available. Gas engineers, electrical engineers and heating engineers together can provide for both domestic and public buildings means of heating which do not foul the atmosphere, and the general use of these systems would, I am convinced, do more for the general happiness of the community than a dozen Acts of Parliament.

The electric supply industry in Great Britain is at present in a state of rapid development, both technically and economically. The economic trend in generating-station practice is towards the large station with a plant capacity of the order of 200 000 kW, and with a site of sufficient area to double this capacity. The generating unit is growing, 40 000-kW machines exist in this country, and manufacturers are prepared to quote for sets of 60 000 kW or over. A plant of this capacity has already been built on Tyneside to an American order, and is now in commission in Chicago.

The reason why development is in this direction is, of course, an economic one. The increase in demand itself forces up the size of the machine. One cannot imagine a power station containing two hundred 1 000-kW sets—its operating costs would be enormous. In addition to this, the efficiency of the plant tends to increase when the size is increased, and, within limits, the cost per kilowatt of plant capacity decreases. The saving in capital is perhaps more vital than the increase in economy.

The fact that the large steam turbine is still the most efficient prime mover affects the economic position of the generating station, for the efficiency of the machine is vitally dependent upon the vacuum obtained by the condensing plant; and, with the present state of the art, to obtain a good vacuum an ample supply of water

is required. This, of course, is common knowledge among engineers, but now that the electric supply business is becoming of interest to the politician and is one in which the man in the street will very soon consider himself a competent authority, it is as well to state here that in this country, where distances from the sea are short and the coal widely distributed, in the interests of general economy it is more important to place our generating stations on our estuaries and larger rivers that it is to build them at the pit-head. The American National Electric Light Association, a very live body which understands the value of publicity, has issued a series of pamphlets on this subject to the general public. Here is an extract from one of them :—

> "Certain publicists have already given fresh currency to the old suggestion that all electricity should be generated at the mouth of the coal mines and distributed from there. They do not know that (1) Electricity can be economically generated by steam, only near a large supply of pure water. For every ton of coal burned in an electric light and power plant 400 to 600 tons of water must be pumped to condense the steam that drives the big turbines. Most coal mines are not near water. (2) The longest distance that electricity can be transmitted economically over wires at present and compare favourably with local power is 250 miles. (3) The cost of generating electricity is only about 20 per cent of the total bill (just as the cost of raising and slaughtering a steer is a small fraction of the cost of your beefsteak). The other 80 per cent is the cost of delivering the service from the power plant to the consumer.
>
> "Electricity is a magic thing—very stimulating to the imaginations of orators and self-appointed friends of the people. But the business men who have built up the electrical industry are not overlooking any bright ideas. They are alive to every possibility of reducing costs and improving service."

The large generating station brings in its wake increasing problems of control and distribution, and certain branches of this side of the electric supply industry have a little difficulty in keeping pace with the rapid growth of the generating station.

Since 1914 the size of the generating unit has grown from about 12 000 kVA to 60 000 kVA, and the size of the generating station has grown from 50 000 kVA to 200 000 kVA. During the same period the rupturing capacity of the largest circuit breakers has grown from 500 000 kVA to not more than 1 500 000 kVA, and the carrying capacity of the largest transmission cables from 11 000 kVA to 18 000 kVA.

In 1914 the rupturing capacity of generating-station switchgear was sufficient to cope with a short-circuit on the station without fault-limiting devices. To-day it is not. Also, in 1914 one transmission cable was able to carry practically the load of one generator. To-day three or four cables are required for this duty.

The capacity of the generating plant has grown more rapidly than the rupturing capacity of the circuit breakers controlling these plants. The 200 000-kVA station has arrived; the 2 000 000-kVA circuit breaker has not. The reason is well known. The generating unit can be thoroughly tested out before being put into commission. The data obtained provides the knowledge for advancement in design. The switchgear manufacturer, however, has never been able to achieve this happy condition of affairs. It is only comparatively recently that any organized scientific research has been done on the behaviour of oil circuit breakers and the rating of rupturing capacity.

The present state of large circuit-breaker design is that it is possible to obtain from most of the reputable manufacturers circuit breakers with a rated rupturing capacity approaching 1 500 000 kVA. This is not a tested-out rating, but is based upon the experience of the designers. The general trend in the use of such circuit breakers is to limit their duty to a figure well inside their rated capacity. This is done by the employment of reactances and neutral resistances, and by designing and arranging the gear to make it difficult for a fault between phases to occur in the precincts of the station.

Pending further experience and knowledge of circuit-breaking phenomena, these methods of limiting the breaking duty, which are well tried out and comparatively simple to apply, will no doubt be the practice in large stations for some time to come. By limiting the fault current at the power station the duty of the switchgear on the system is also eased. This is very desirable, because it is not economically possible to employ maximum-rated circuit breakers at all points of high-tension service.

The recent development in switchgear which is most interesting to us on Tyneside is that of the wider adoption of switchgear of the metal-clad type for first-grade duty. This type of switchgear originated on Tyneside, is now built by most of the important switchgear manufacturers in England for use at all voltages up to, and including, 33 000, and I believe that I am speaking truthfully when I say that there are some who have ambitions to build metal-clad gear for higher voltages than this. Logically this type of switchgear should, and in practice it does, tend to follow the development in underground cable design, for it is a fitting termination to the lead-sheathed cable.

Before leaving the consideration of heavy-power switchgear I should like to plead for an increase in the national facilities for research in circuit-breaker phenomena. Excellent work is being done under Mr. Wedmore's guidance by the Electrical Research Association, but the scope of their research would be considerably increased if they were allowed to "experiment" with a really large plant capacity. The larger manufacturers of switchgear in other countries have themselves realized the necessity of expensive heavy-powered testing plant, and it is time that a similar plant was erected in this country. Could not the larger switchgear manufacturers combine to provide a proving house which would be worthy of the industry and the country? The organization to make such a venture possible already exists. A well-equipped research

laboratory would hasten the day, which I feel is bound to come, when the ferocious arc (our modern Lambton worm), which is now a necessary evil, will be at least tamed, and the breaking of an electrical circuit will not be explosive.

The art of cable-making and cable-using is at present in a wonderfully interesting state of development, and although it is, perhaps, true that this section of the industry lags behind those of generation, transformation and overhead transmission, yet the increased knowledge of dielectric phenomena now available has so widened the field of vision of the cable engineer that he is endeavouring to rival the feats of the pole-line man and to turn out cables for use at voltages which, in the past, could only be applied to bare conductors hung on insulators.

The economic problem is, of course, well known. High voltages are advantageous, not only to transmit power over long distances, but also to transmit large quantities of power into the centres of our large cities. Roughly speaking, the economic unit of transmission corresponds to the unit of generation, and, whereas in the past we were content to carry some 10 000 kW per line, we shall in the near future carry on one line some 50 000 or 60 000 kW, which will mean the use of three-phase voltages of 100 000 and over.

Whether the cable makers will achieve this end by the use of lead, paper and oil, it is perhaps too early to say. If a consistent, imperishable, homogeneous and flexible dielectric should be discovered it is probable that it would, in time, supersede paper and oil.

Power-transformer design continues to keep pace with the developments in other sections of the industry. Transformers can be built of capacities equal to those of the largest generators, and for use at voltages as high as can be dealt with by the transmission lines. Moreover, the modern large transformer is usually sturdy enough to withstand the stresses of short-circuit and surge potentials.

One of the primary problems of transformer design is that of the cooling of the windings to maintain the insulation, and this resolves itself into knowing all about the "hot spots" which determine the rating of the transformer. What the user wants to know is the relation between the "hot spot" temperature and the temperature of the oil.

There is not much published information on this subject in this country, and manufacturers as a body do not yet encourage the loading of their transformers on the basis of oil-temperature measurements. The point is one of great importance to the transformer user, for if degrees Centigrade and not amperes were the measure of the safe load on the plant it would generally result in the reduction of the capital cost of a service. If the manufacturers would sell their transformers on the understanding that they would be safe so long as the temperature of the oil as indicated on the thermometer provided with the transformer did not exceed a stated figure, then full advantage could be taken of the variations of load factor and ambient temperature. Rotary converters for traction work in automatic substations are entirely controlled by temperature-indicating instruments. Then why not transformers? The time is ripe for the distribution and use of such knowledge.

In the largest transformers the heat generated by the losses is extracted from the oil either by water or by forced air. A characteristic of the time, however, is the rapid increase in the sizes available of "self cooled" transformers. Transformers up to 10 000-kVA capacity can now be obtained which keep themselves cool by the natural circulation of the oil through nests of pipes or radiators hung on the sides of the tanks containing the transformers.

Overhead transmission lines as now constructed are remarkably reliable. The mechanical and electrical problems of design are well understood and on the first-grade lines throughout the world little trouble is experienced from the effects of wind and weather.

The main enemies to continuous service are birds and lightning, and, of the two, birds are perhaps the deadlier. We know of bird troubles in this district, and "crow guards" are an essential part of the construction of our high-tension lines. In India many of us have heard of delays to service caused by crows building nests on cross-arms and pole tops, the nesting material, sad to relate, sometimes being the scrap ends of armouring wire left from underground cables being laid in the district. On the famous Big Creek 220 000-volt line in California the most numerous interruptions to the service in the early days were caused by the matutinal evacuations of large vulture-like birds who had spent the night on the cross-arms above the insulator strings.

Lines designed for 100 000 volts are practically immune from lightning troubles. It is uneconomic, however, to insulate all lines and the apparatus connected to them for 100 000-volt working, and so, at the moment, the lightning problem resolves itself into the protection of the line insulators against destruction from arc-overs, and the protection of the insulation of the apparatus connected to the line.

The study of lightning and the effect of lightning on transmission lines is still being actively pursued, particularly in Sweden and America. The wider knowledge of high-frequency phenomena now available from radio research and experience also helps in the attack on the problem, and it is probable that lightning and surge protection will ultimately be achieved by connecting, directly in the line, apparatus which will absorb the energy of the surge before it reaches the apparatus to be protected and without any power current leaking to earth, that is, the line will not be shut down even temporarily when under the influence of lightning.

The problem of the day, however, in this country is not the construction of first-class high-grade high-pressure lines, but the construction of cheap high-pressure distribution lines which would enable the supplies to be given economically to farms, villages and sparsely loaded districts. Small capital cost is essential for this class of work, but it is difficult to say how this can be attained under the existing Regulations covering the construction of high-pressure lines.

The use of conductors of high-tensile metals such as

steel and silicon bronze in place of copper or aluminium helps a little towards cheapening the lines, but it seems impossible in this country ever to get the cost down to the £200 or £300 a mile so common in America. We should be pleased if we could only get lines constructed at double this figure.

There has been much said previously both in the Press and from the platform on the desirability of easing the various Regulations and restrictions which govern the construction of British overhead lines. These Regulations and restrictions certainly do keep up the cost of our high-tension overhead lines, and reasonable proposals for their modifications are worthy of consideration by the authorities.

The cost of rural high-tension overhead lines could be considerably reduced if the figures for ice-loading specified in the Regulations were modified. People are not often working in the fields when ice-loading conditions prevail, and therefore I suggest that the danger to the public would not be seriously affected if high-tension lines across fields and along hedgerows, away from the public roads and railways, were constructed to meet the reduced ice-loading allowed in the Regulations for low-tension lines. This modification alone would bring down the cost of rural lines some £50 or £80 per mile, and in view of the rarity of the worst ice conditions in this country, and the fact that our low-tension lines seldom fail from this cause, I feel that the suggestion is reasonable and worthy of consideration.

For transmitting large blocks of power, overhead lines are less than half as costly as underground cables. The conclusion one draws from this is that in a country where the demand for power is large and the available capital is scarce the use of overhead lines should be considered wherever possible, even in the centres of the towns.

There are, of course, obvious difficulties in the erection of transmission lines in the centres of densely populated districts, but if the roads are not available there are often routes into towns such as those along railways and canals which are quite feasible for overhead work, and I maintain that an enlightened but hard-up people, such as we are, should allow these problems of power supply to be settled on their engineering merits, keeping in mind the service given rather than antiquated legal prejudices and æsthetic standards which are too often false.

Probably the most notable development during the last few years is the automatic converter substation. The general tendency in power and lighting distribution is to give alternating current for all services, but for railway work—owing probably, and if so rightly, to the fact that for the usual frequencies of power supply a satisfactory alternating-current traction motor is not yet obtainable—pending this desirable development it is necessary to convert the power as generated from alternating to direct current. This means the employment of substations containing rotating plant.

The automatic substation has been made possible by modern improvements in the design of rotary converters and the protective and control gear for rotary converters. It is now possible to obtain commutating machines which are practically unaffected by dead short-circuits on their terminals. With apparatus such as this a converter substation can now be run entirely unattended; it takes charge of itself and runs accurately to meet the load conditions.

It is now generally accepted that a properly designed automatic substation, because it eliminates many of the chances of human error, which occur particularly at critical times, is more reliable in its service than a manually operated substation, and its employment can be economically justified, not only in districts where the standard of intelligence and the wages of the substation attendants are high, but also in districts where the standard of intelligence and the wages of the substation attendants are low. For example, the automatic substation is commercially and technically sound both in America where labour is costly and in India where labour is cheap.

The long-tried and popular rotary converter has, during the last few years, received a challenge from a new rival—the mercury-arc rectifier. At the present time the capital cost of a rectifier installation is not less than that of a rotary-converter installation to do the same duty, and its claims for justification can only be based on such factors as efficiency, simplicity and reduced maintenance costs. Whether these factors are sufficiently strong to eliminate the more tried-out, old-established rotary converter for railway work, it is perhaps too early to say at the present time.

Whether the electric supply industry will continue to prosper depends, of course, primarily upon the general state of industry of the country and, secondly, upon the education of the public in the uses of electricity—that is salesmanship. The number of units generated per head of population in America is more than three times the corresponding figure in this country, and the curve is still rising.

It is possible in these days that the electricity used in any manufacturing country is a measure of the output of the industries of the country, and whether we shall ever approach the American figures of consumption of electricity depends very much upon whether we are able to bring the output of our factories and mines up to the American standard.

Our aim must always be "Service," a hackneyed term but nevertheless a true one. We must always remember that the justification of our calling is that we improve the lot of the people, and we do this, not only by increasing the product of their industry—a most essential thing at the present time—but also by reducing drudgery and toil.

Amongst ourselves we have to aim at continually increasing economies, not only in the use of coal but in the use of capital. The pound of coal must be made to hand over its maximum of usable energy, and the pound sterling its maximum of service.

We electrical engineers are a young fraternity. One of the joys of our existence is that we have no tradition. What we shall do to-morrow we never have done before.

Let us not forget that we are young, and do not let us affect the foibles of old age before our time. Toil

and adventure are still our part, not limitation of output and over-much "Safety First."

We are told of the ancient Greek that:—"His methods were direct, his endurance unlimited and his energy tireless. He could call a spade a spade without self-consciousness, he could worry at a problem until he solved it, or thought he had solved it, and he was always ready to consider and deal with something new." *

I have delved into an ancient field and I find that I have unearthed, unsoiled and unscarred, an elegant model of a modern electrical engineer.

* STANLEY CASSON: "Ancient Greece" (Oxford University Press).

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE: CHAIRMAN'S ADDRESS

By A. E. MALPAS, Member.

"ELECTRICITY IN THE ARTS."

(*Address delivered at* LIVERPOOL, *2nd November*, 1925.)

I have been asked to choose as my subject to-night that of electricity as applied in the electro-chemical and electro-metallurgical industries.

The reactions involved can be divided into two classes: (1) Those which absorb energy, and (2) those which give out energy, usually as heat, while the reaction is taking place.

Under class (1) fall such processes as the manufacture of calcium carbide, the oxidation of atmospheric nitrogen, the extraction of metals such as sodium, aluminium and magnesium, and electrolytic processes in general.

The second class includes the exothermic reactions such as are involved in the manufacture of calcium cyanamide, and the oxidation of ammonia to nitric acid.

It is obvious that in the short time at our disposal this evening it will be impossible to review at all completely such a wide field of activity, and it will perhaps be as well to abbreviate the descriptive matter and illustrate the subject as far as possible by means of lantern slides.

THE MANUFACTURE OF CALCIUM CARBIDE AND ITS DERIVATIVES.

It is within the memory of most of us how Moissan, the French physicist, in an endeavour to produce artificial diamonds, failed in his immediate object but laid the foundations of the modern processes involving the use of the electric furnace. The most important of these is that of the carbides, principally calcium carbide which forms the starting point of raw material for a large series of organic compounds including acetylene, now so largely used for lighting and welding purposes.

The fundamental equation is quite simple

$$CaO + 3C = CaC_2 + CO$$

and the process consists in heating these two materials together in the electric furnace. The reaction with water gives acetylene

$$CaC_2 + 2H_2O = Ca(OH)_2 + C_2H_2$$

in which the lime originally used reappears as a waste product.

The largest outlet for calcium carbide is in the manufacture of cyanamide, by treatment at a temperature of about 1 000° C. with nitrogen gas, obtained usually by the rectification of liquid air.

The reaction is

$$CaC_2 + N_2 = CaCN_2 + C$$

one half of the carbon content being thrown out of combination in the process. The air after being dried and purified is refrigerated to about $-194°$ C., when the two constituents, oxygen and nitrogen, can be separated by means of a rectifying column.

Other derivatives of carbide are cyanide

$$CaCN_2 + C + NaCl = CaCl_2 + 2NaCN$$

which is used on a large scale for the extraction of the precious metals in the gold-mining districts and for the fumigation of ships, etc.

The capacity of the American Cyanamid Company at Niagara Falls is 75 000 tons per annum, and other plants in Germany and elsewhere are in operation on a more or less similar scale. The world capacity for the production of cyanamide is estimated at about 300 000 tons per annum.

Although at least 40 different compounds are produced from cyandamide as a raw material, probably the largest outlet is as nitrogenous fertilizer, and in this field it enters into competition with Chile saltpetre.

Ammonia also is obtained from it

$$CaCN_2 + 3H_2O = CaCO_3 + 2NH_3$$

by heating under pressure in presence of an alkali.

Nitrates can further be produced by the oxidation of the ammonia by means of the Ostwald process referred to below.

On the screen are shown lantern slides from one of the Norwegian water-power plants on the Hardanger Fiord, which was extended in 1914 to a capacity of 200 tons of cyanamide per day, absorbing some 50 000 h.p. for the manufacture of the carbide and some 6 000 h.p. for the conversion to cyanamide.

Running on 100 per cent load factor it is probable that the cost of generation does not exceed 0·04d. per unit. The selling price of the high-tension energy metered at the works transformer substation was 0·07d. per unit on the pre-war contract.

Oxidation of Atmospheric Nitrogen.

In this process a means is found to avoid the somewhat roundabout method involved in the carbide-cyanamide process, by combining the two constituents of the air directly to form nitric acid. The reaction is quite simple

$$N_2 + O_2 = 2NO - 43\,000 \text{ calories.}$$

The principal adopted is to force a current of air into intimate contact with a high-tension arc and to withdraw and cool as rapidly as possible the nitric oxide so formed, in order to prevent decomposition of the product, since the equation is a reversible one.

Various types of furnaces, etc., are shown in the lantern slides.

The home of this process is also in Norway at Notodden, where over 400 000 h.p. is installed and 13 000 tons of air are blown through the furnaces every 24 hours. About £8 000 000 has been spent on the development of the power plant and the equipment of the factories, which is equivalent to about £32 per kilowatt installed.

Owing to the low efficiency of conversion, only $1\frac{1}{2}$ per cent of nitrous oxide being formed, a large quantity of heat is carried away by the gases leaving the zone of the arc. The air blast is regulated to give a temperature of about 1 200° C., above which nitric oxide is decomposed. The gases leave the furnace at this temperature and are cooled down to 200° C. by passing through steam boilers. On cooling, a further reaction takes place

$$2NO + O_2 = 2NO_2 + 27\,000 \text{ calories}$$

more oxygen being taken up. The gases are finally absorbed by passing through a series of towers over which weak nitric acid is circulated, the final equation being

$$2NO + 3O + H_2O = 2HNO_3.$$

The heat recovered by the steam boilers per kilowatt-year expended in the furnace is equivalent to that of one ton of coal and is sufficient to supply the whole requirements for steam of the chemical processes involved.

The nitric acid produced is used in producing calcium nitrate by reaction with limestone, ammonium nitrate and other products. The calcium nitrate is known commercially as Norwegian saltpetre in contradistinction to the sodium nitrate obtained from Chile, with which it also enters into competition as a fertilizer.

Other Solutions.

Other solutions of the nitrogen problem have been found, more particularly that known as the Haber process and its modifications, in which nitrogen and hydrogen are combined directly to form ammonia by means of a suitable catalyser.

$$N + 3H = NH_3 + 11\,900 \text{ calories.}$$

Since this reaction is exothermic, no great amount of power is required to maintain it once the reaction is started, so that the process is one that can be economically worked without the aid of cheap water power. The heating element consists of a coil in the reaction chamber through which current is passed for the control of the temperature of the reaction.

There are certain mechanical difficulties that have had to be got over in applying the equation in practice, for example the difficulty of working a process at a pressure of 200 to 1 000 atmospheres and a temperature of 500 to 700° C. These difficulties have, however, been solved in different ways by Haber and, later, by Claude in France and by Casale in Italy. The process is also being worked now on a large scale in England.

Ostwald Process.

This was originally an electric process for oxidizing ammonia to nitric acid. The equation is

$$4NH_3 + 5O_2 = 4NO + 6H_2O$$

the nitric oxide on cooling and treating with water giving nitric acid. This reaction is exothermic and the original apparatus has been much simplified and is now worked without the aid of electricity.

Electrolytic Production of Gases.

We come next to consider a class of reaction quite different from any of the foregoing, namely, one in which the changes produced by the electric current take place in aqueous solution, and here it is that we begin to refer to ions.

The simplest case is that of water itself. Having been made conducting, preferably by the addition of caustic soda, the alkali is electrolysed, giving OH (the hydroxyion) at the anode and Na (metallic sodium) at the cathode. Interactions take place, finally, giving oxygen at the anode and hydrogen at the cathode. Thus

$$2OH = H_2O + O \text{ and } Na + H_2O = NaOH + H.$$

This is one of the oldest applications of the electric current, but one that is to-day becoming of great industrial importance. The mixed gases form, of course, a detonating mixture and must be kept separate.

Lantern slides show the Janbert cell, the Knowles cell and the column cell. The Knowles cell is to-day probably the most widely used of the many variations of the early types that have been evolved from time to

time, and it is gratifying to note that this is almost a local product, in that it is manufactured on a large scale at Chester.

As a result of Sabatier's work on the hardening of oils by means of hydrogen, on which our supply of synthetic butter so much depends, the demand for hydrogen largely increased and was met partly by electrolytic methods and partly by other means, notably the Lane steam-iron process. To-day the electrolytic method appears to be displacing the other processes.

Still more recently, the demand for synthetic ammonia has increased to such an extent as to necessitate further supplies of hydrogen and, therefore, plant for producing it. Knowles cells capable of absorbing 20 000 kW and producing 8 tons of hydrogen per day are at work, or shortly will be at work, not only in England, but also in France, Italy, Russia, Chile and other countries.

Of minor importance, but still of interest in view of Moissan's researches, is the fact that there is a small Knowles installation erected at Bodio in Switzerland for the production of synthetic rubies. Oxy-hydrogen muffle furnaces are used, the supply of gases being produced electrolytically.

Taking the cost of energy at 0·1d. per unit, the cost of hydrogen represents one halfpenny per metre cube for the power used.

Chlorine.

Other gases besides hydrogen are produced electrolytically by using an appropriate solution. The most commonly used is sodium chloride, giving chlorine at the anode and caustic soda and hydrogen at the cathode. In some cases sodium carbonate is produced instead of caustic soda.

There are three types of cell in use: (1) the flowing-cathode type, (2) Bell cells, and (3) diaphragm cells. Of these, the last-mentioned is most widely used to-day, although the Italians appear to be developing more along the lines of the mercury cell.

In the flowing-cathode type a stream of mercury is caused to flow at the bottom of a trough below the anodes suspended above it, the whole being immersed in the particular salt solution used. In the case of sodium chloride the passage of the current liberates chlorine at the anode and metallic sodium at the mercury cathode, with which it amalgamates and is removed from the anode compartment. The amalgam on treatment with water gives the hydrate NaOH, with liberation of hydrogen.

Of the diaphragm cells there are many varieties, of which the best known are the Nelson and the Gibb cell.

In pre-war days, chlorine was absorbed in slaked lime and marketed as bleaching powder. During the war this gas was largely used in liquid form in chemical warfare. It is one of the most easily liquefiable of the elementary gases, condensing under atmospheric pressure at a temperature of about − 40° C. To-day it is becoming more the practice to use chlorine in the liquid form, thus displacing to some extent the more cumbersome bleaching-powder method of transportation of the gas. The largest installation in the world is said to be the plant put down by the United States Government at Edgeware Arsenal, where 3 500 Nelson cells were installed for war purposes to give 100 tons chlorine per day and the equivalent of caustic soda.

Many other products are produced electrolytically, such as hypochlorites, chlorates, and perchlorates, which are obtained by suitably varying the conditions of the process or the design of cell.

The lantern slides show the evolution of the process.

Extraction of Metals.

The cells used for the extraction of sodium, calcium, magnesium and aluminium, work with a fused electrolyte at temperatures ranging from 300° to 1 000° C.

Sodium.—The Castner sodium cell shown uses fused caustic and works at about 320° C.

Fused salt, which requires a much higher temperature of about 800° C., is said to be successfully used at Basle, the cell being heated internally by electric resistances.

The Ashcroft cell uses a double compartment with fused lead to form a sodium-lead alloy, chlorine being liberated in the first compartment and the metal sodium being discharged from the second.

Magnesium.—Magnesium is produced in a cell of much the same type using fused lead as a carrier. It is said that cells for the production of magnesium have been operated by the Magnesium Company at Wolverhampton at 5 000 amperes, each taking 5 volts, giving an output of 100 lb. of metal per 24 hours, or 6 kWh per lb. of metal.

It is thought that magnesium has a future before it for the production of light alloys and that it may some day compete with aluminium.

A large plant is now in course of erection on the Continent for the production of 80 tons per week of the metal.

Calcium.—Metallic calcium is obtained in a cell of the type shown on the screen.

The output of these three metals being relatively small it is probable that no great amount of power is absorbed in their production. The case is, however, different with aluminium, the output of which has grown to very large dimensions.

Aluminium.—The electrical process for the extraction of aluminium was first operated by the Pittsburg Reduction Company in America in 1889, a similar process being operated in France about the same time. The reaction itself is, as usual, quite simple.

$$Al_2O_3 + 3C = 2Al + 3CO$$

the raw materials used being bauxite and carbon. Bauxite is mined in the south of France, being named from the town of Baux where the most suitable quality was first obtained. To-day large deposits of suitable material have been discovered in other parts of the world. The crude material contains about 60 per cent alumina, and to refine it sufficiently for use requires the expenditure of 8 tons of coal per ton of finished metal. This, no doubt, explains why the manufacture of aluminium has developed to the extent that it has done in England, the ore being first brought to the

coal-fields for refinement and afterwards treated in electric furnaces at one of the hydro-electric power plants.

The refinement process consists in treating the crude ore with caustic soda and filtering and roasting. At the furnace each ton of metal requires 25 000 kWh, so that at 0·1d. per unit the cost for current comes out at £10 per ton.

Aluminium was first isolated in 1828, but it was not until 60 years later that the electro-chemical process for its economical extraction was more or less perfected. The process consists in the electrolysis of a 15 per cent solution of Al_2O_3 in a bath of fused cryolite which is a complex sodium-aluminium fluoride, Na_3AlF_6. The carbon used in the reaction is supplied largely by the amorphous carbon anodes, the wear and tear of which is very great and supplies practically all the carbon required by the chemical equation.

The furnace used is of simple rectangular construction and is lined with carbon to form the cathode, the anodes being of amorphous carbon suspended in the fused electrolyte. Each furnace may be 8 ft. × 4 ft. 6 in. × 2 ft. deep and will carry 8 000 to 10 000 amperes at about 6 volts. The working temperature is about 1 000° C. and the current efficiency about 75 per cent.

The molten aluminium, as it is formed, sinks to the bottom of the bath and is run off from time to time by means of a tapping hole.

Members of the Institution have at different times visited both the hydro-electric installations in this country producing aluminium. As pointed out earlier, the proximity to the coal-fields makes aluminium a more economical proposition for the small amount of water power available in this country than would be the case with other electro-chemical products. The two installations to which I refer are that of the British Aluminium Company at Kinlochleven and that of the Aluminium Corporation at Dolgarrog, North Wales.

Some of the lantern slides show general views of Kinlochleven and the power house where 35 000 b.h.p. is installed. The new installation at Lochaber will bring the total capacity up to 107 000 b.h.p. in a year of average rainfall.

The Dolgarrog installation is capable of extension up to approximately 33 000 electrical h.p.

Both plants together should, when fully loaded, be able to turn out about 36 000 tons of metal per year and thus supply a large part of the world's consumption, which was said to amount to 45 000 tons in the year 1911.

From figures published in 1910 * it was estimated that the cost of power delivered to the Kinlochleven factories was 0·1d. per unit, including all charges from the dam to the switchboard, and that the cost would fall as the load increased. The cost of the power plant is given as £600 000 at that date, and of the chemical plant £650 000, the equivalent of £17 and £18·5 per kilowatt installed respectively.

It is of interest to record that an installation built during the war at one of the hydro-electric plants in Italy for the production of aluminium has since been shut down and is turning over to the manufacture of synthetic ammonia.

It would seem, therefore, that, so far as aluminium is concerned, we shall be able to hold our own, but that in order to foster other electro-chemical industries everything possible should be done to reduce the cost of power production in this country. This is a large question which does not fall within the scope of my subject, but it is one that we should always have in mind, and our constant endeavour should be in the direction of the reduction of power costs.

[The Address was illustrated by 50 lantern slides.]

* Discussion on "The Hydro-Electric Plant in the British Aluminium Company's Factory at Kinlochleven," *Minutes of Proceedings of the Institution of Civil Engineers*, 1911-12, vol. 187, p. 97.

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By A. G. Ellis, Member.

(Abstract *of Address delivered at* Manchester, *3rd November*, 1925.)

In this Address I propose to put before you some considerations which, I think, are at the moment worthy of attention, as concerning the well-being of the electrical industry.

Although recent progress compares favourably with progress before the great war, and the electrical industry has been remarkably well maintained in the face of general depression in other engineering trades, it is essential to its stability and success that more rapid and immediate expansion be attained.

Since the World Power Conference held at Wembley last year, electrical engineers have begun more generally to realize the position of Britain as compared with other countries with regard to electrical development. It is now becoming common to compare different countries on the basis of what might be termed an "electrical development coefficient," viz. the consumption of electrical energy per head of population per annum.

The scope for expansion of the use of electricity in this country is emphasized by realizing that the figure for Britain is only about 130 B.O.T. units per annum per head of population; * in America (U.S.A.) the consumption is over three times this figure, in Switzerland over six times, and in Norway, I believe, even higher.

Of course, it will be said, such results can easily be reached in countries having the advantage of cheap water power. The latter is, however, rather a fallacious and elusive thing; and an examination of the facts shows that the British consumer pays, on the average, less for his electricity than many of his Continental neighbours in "water-power" countries. The cost of harnessing the water power is largely responsible for this. The reason for the extensive use of water power (apart from the lack of coal) is probably a psychological one; the potentialities of the river or waterfall are thrust daily before the population, and their utilization for electric power generation is a clean and wholesome business, free from coal mining, stoking, ash-handling and the smoke nuisance.

There is no doubt that electricity is now recognized as a vital economic factor in the welfare of the nation, and the appointment and work of the Electricity Commissioners has stimulated this aspect. The late Government had in preparation a scheme for the further coordination of electricity supply, and there are indications that this is likely to fructify under the present Government. The Electricity Commissioners † have estimated that if all the electricity generated in the country were produced by modern and efficient stations the total saving in coal would amount to some 20 per cent, or for the same coal consumption 25 per cent more electrical energy might be generated. If the granting of wider and compulsory powers to the Commissioners can effect this, there is sufficient reason for legislation to this end.

* This represents energy sold; the total energy generated by all public suppliers and private plants is of the order 200 B.O.T. units per annum per head.

† Fourth Annual Report, p. 9.

The anticipated new legislation with regard to electricity supply will again bring electricity prominently to the public notice, and the electrical industry would be well advised to take the opportunity of concurrent action in the education of the public. The occasion would be opportune for a widespread national campaign organized, I suggest, jointly by the Electrical Development Association (which is already doing excellent propaganda work), the I.M.E.A., the B.E.A.M.A., the newly formed Women's Electrical Association, and this Institution, to carry the gospel of electricity to the multitudes.

It will doubtless be argued that the speeding up of electrical development is mainly a financial question. This though true is not an impediment, as there is no difficulty in raising money for electricity supply undertakings. The capital expenditure on electricity supply has practically doubled during the past five years, and the dividends of the supply companies have shown a steady increase, now averaging over 6 per cent.

Progress in the electricity supply industry during the past five years (ending March 1925) has resulted in an increase in the total kilowatt capacity of plant installed from about 2½ million kW to 4¼ million kW; the total energy generated from 5 167 million to 7 415 million B.O.T. units per annum (this includes generation for railways, tramways, etc., in addition to public supply), and the total energy sold from 3 086 million (for 434 reported undertakings) to 5 124 million B.O.T. units per annum (for 491 reported undertakings).* The latter figures represent an increase of 66 per cent for the 5 years; but a strict comparison cannot be made, as the available statistics for each year do not relate to exactly the same number of undertakings. Allowing for this divergence, it would appear that the increase in units sold for the past year (March 1924–March 1925) has been roughly equal to the total increase for the four preceding years put together, which is a most encouraging result.

The new plant involved has been almost exclusively of home manufacture, and, so far as the manufacturers are concerned, there is no doubt that they are ready to meet any demands for new plant put upon them due to speeding up of electrical development.

During the past five years great strides have been made in "heavy" electrical manufacture, and it may safely be asserted that the British manufacturer has

* I am indebted to the publishers of Garcke's "Manual of Electrical Undertakings" for the 1925 figures.

caught up his "angle of lag" of some 10 to 15 years, and is now in phase with the American and Continental manufacturer. This is testified by the important orders secured by British manufacturers in the Colonies and in Russia, against American and Continental competition.

Recent progress relates principally to large turbo-generators, extra-high-tension transformers and switch-gear, and automatic and supervisory control of stations. This country has recently exported a 50 000-kW 1 800-r.p.m. turbo-generator, and 35 000-kW and 40 000-kW units at 1 500 r.p.m., also for export, are in hand. In extra-high-tension transformers and switchgear for pressures of 100 kV and over, British manufacturers have recently built, for export, apparatus aggregating over half-a-million kVA.

At home we have outdoor substation installations of British manufacture in operation at 66 kV and 33 kV, some of the latter plant having withstood for several years the most severe test possible for outdoor electrical apparatus, viz. the climate of Manchester. Testing-transformers of 300 kV and 500 kV, for the commercial testing of cables and insulators, have been built and are in successful operation, and 1 000 000-volt testing-transformer equipment is under construction.

Perhaps the most remarkable development for some years is the automatic substation equipped for wholly automatic or remote supervisory control. The first automatic substations in this country were put down only three years ago, and the excellent service obtained is vouched for by the engineers concerned and by the rapid spread of this type of plant.

The automatic or remote controlled substation offers a solution of many distributing problems in congested or isolated areas where either the cost of land and buildings or attendance is prohibitive. As an illustration of the saving in space and buildings, I might mention a subterranean station which is being put down in London, containing two 300-kW rotary converters with fully automatic control. This substation measures 28 ft. × 15 ft. and is entered through a 5-ft. × 3-ft. manhole in the pavement.

Rotary converters up to 4 500 kW for 1 500-volt d.c. traction load, with automatic control gear, have been supplied to the Colonies. These machines are capable of supplying direct current two minutes after receiving the starting impulse.

The previously prevailing impression that Britain was not capable of doing these things is now dispersed, and this country is recognized as an established competitor in contracts for large and extra-high-tension gear, which hitherto went without question to America or the Continent. However, in many lines of standard electrical machinery and apparatus, under present conditions, the British manufacturer compares unfavourably with the American and German manufacturers. The reason is not far to seek; it is the advantages derived from the much greater total volume of electrical manufactures in these countries. The cure for this is to boost up the total electrical business in England, and get the benefits of manufacturing in larger quantities.

To achieve this we have to look to expansion of the home market. We are already in the position of exporting about one-third of our total electrical manufactures, whereas the U.S.A. export only about one-tenth of their total, although the total cash value of the American and British electrical exports is about equal.

Of the total exports of electrical machinery and apparatus (including cables) from five leading industrial countries in 1924 (amounting to £53 000 000) Britain supplied 29 per cent, U.S.A. 31 per cent, and Germany 27 per cent, whilst France and Switzerland were responsible for practically the remaining 13 per cent.* Thus, we are at present securing with the U.S.A. and Germany practically an equal share of the world's total electrical business; and, although our proportion has shown a slight increase during the past few years, no increase of great magnitude is to be expected in the near future.

Competition in the Colonial markets is very keen, and will become still more severe as soon as our principal competitors, America and Germany, no longer absorb the bulk of their electrical manufactures in their home markets, as they do at present.

Another influence which may have a serious effect on the Colonial markets for electrical apparatus is the possibility of protective legislation, on the lines of the anti-dumping duties in Australia, being adopted by other Dominions. The aim and effect of these duties is to create and build up a manufacturing industry in the country concerned. We have, therefore, for salvation to look to the home market to develop in similar proportions to those obtaining in America and Germany.

Intimately bound up with this matter is the imperative necessity of cheaper cost of production of electrical apparatus. Without entering into the complexity of factors which are involved in this question, I consider that the key-note is quantity production; and herein the important factors with which we are concerned are: (I) increase in demand, and (II) standardization.

(I) Increase in Demand.

In the industrial field further application of electricity to mills and collieries is making steady progress, judging by the number of industrial electric motors produced annually. No great expansion is to be looked for, however, until a general industrial revival sets in in earnest. There are, however, new fields of application to be exploited, such as electric ovens for bakeries and electric heating processes in other industries.

An intensive programme of railway electrification would react favourably on the development of public electricity supply.

The Southern Railway group have given a lead in their programme of extensive suburban electrification, which is the largest piece of electrification yet undertaken in this country, involving 647 track-miles and costing nearly £8 000 000. Apart from this, however, in spite of the good case for main-line electrification made out by Colonel O'Brien in his paper last Session, there is little indication that any comprehensive efforts will be made in the near future.

We have, therefore, to look for more immediate expansion to the domestic and rural fields of application.

In the domestic field the importance of the heating

* The contribution of other industrial countries was only a small percentage.

and cooking load as a means of improving the load factor renders the consumer taking power for these purposes as well as lighting, the most valuable for the supply undertaking to cultivate. The all-electric house (on which we are to have a paper and discussion this Session) should be established as an accepted integral part of any new housing scheme. In this matter great assistance can be rendered by the Women's Electrical Association, recently formed "for the promotion of wider use of electricity in the service of Women."

Another matter worth more attention is the simplification of house wiring and the provision of facilities for "free" wiring. A small domestic consumer who hesitates about capital outlay for an electrical installation would not feel the payment of the interest on, or repayment in instalments of, the capital, if included in his quarterly electricity bill.

Development of rural electricity supply for agriculture is a field which is at last receiving in this country the attention it deserves. The politicians have already started to bring electricity into their schemes of land policy, so it behoves the engineer also to get busy. Nearly one-half the total area of Great Britain is farm land, comprising nearly half a million farms and small holdings. At present there are, in Great Britain, only about 400 farms electrically equipped, although it is anticipated that this number will be doubled in another year. Here we lag far behind other agricultural countries, which are jointly responsible for about 1 000 000 electrically-equipped farms throughout the world. There is thus awaiting exploitation in this country an enormous new field, of which the potential total demand for electrical energy is estimated at between 500 million and 1 000 million B.O.T. units per annum.

Apart from the problem of providing cheap and abundant power supply, the principal matters calling for present consideration appear to be :—

(1) The education of the farmer in electricity, and the electrical engineer in agriculture.

(2) Close co-operation between the supply undertakers, the Commissioners and the Post Office to remove any difficulties in the way of the running of inexpensive overhead transmission lines.

(3) The manufacture of simple and inexpensive switch and transformer installations for tapping the high-tension transmission lines.

(4) An adequate system of hire-purchase and maintenance of electrical plant for farm installations.

An enormous amount of educational work among farmers has already been done, and I may mention the pioneer work of Mr. Borlase Matthews. On his model electric farm at East Grinstead, Surrey, which has been in operation for six years, electricity is utilized for 67 different purposes, of such variety as lighting the byres, milking, ploughing, producing artificial daylight for egg-laying poultry and making hay while the sun does not shine. The economy of labour and reduction in wastage obtained, results in such an increase in food production per man as to justify the question being considered as a national one.

Cheap power supply is largely dependent on the cost of transmission lines and of tapping them. Any revision of existing rules and regulations should be in the direction of facilitating the obtaining of way-leaves for, and simplifying the standard of construction of, overhead high-tension transmission lines, rather than in the framing of special regulations; and it is to be hoped that the Electricity Commissioners will exercise a beneficent influence in this direction. Certain regulations are no doubt requisite to ensure the general safety of the public and livestock, but they should be as simple and unrestrictive as possible. It can surely be left to the common sense of electricity undertakings who are endeavouring to develop the rural supply to see that any lines and installations they put down are both safe and sightly, constituting, as such installations do, one of the best forms of propaganda.

The setting up of small industries on the land, or transference from the towns, should be stimulated, so as to improve the load factor of the farm load and conduce to economic supply.

It is appropriate that I should, by way of example of what can be done with small rural consumers, refer to the pioneer development work in rural supply which has taken place recently within our own area, on the Mid-Cheshire Electric Supply Co.'s system in the Northwich district, and also on the Chester Corporation system.

On the Chester system there are some 15 miles of three-phase 6 600-volt overhead line, with 13 open-air substations, stepping down to 400/230 volts and supplying 20 miles of 4-wire overhead distribution lines. The area served is about 70 square miles and already nearly 600 consumers are connected, representing a load connection of 952 kW.

On the mid-Cheshire system, with its centre at Northwich, there are in use or under construction 21 miles of overhead three-phase transmission line at 33 000 volts, covering an area of 120 square miles and designed to feed 3 towns (Knutsford, Winsford and Middlewich) and about 25 villages within a radius of about 6 miles. The village and country lines in use represent a load of about 150 kW and 100 000 units sold per annum, but within a few months this will increase. The charges in the country areas are the same as in Northwich and the other towns.

For distribution to the small towns and larger villages adjacent to the transmission line the pressure is stepped down from 33 000 volts to 400/230 volts, three-phase, by outdoor transforming units of the simplest possible composition, comprising oil-immersed self-cooled transformer, horn-type air-break switches, and horn-type high-tension fuses. The smaller villages are dealt with in connection with country lines, which are supplied at 3 300 volts single-phase from outdoor substations on the 33 000-volt routes.

The country lines feed villages, mansions and farms through pole-mounted single-phase transformers at 3 300/220 volts. The cost of running these country lines for three-phase distribution would be prohibitive; and no difficulty has been experienced in the use of single-phase motors, as they are rarely required to start under load.

Even with single-phase two-wire lines the cost of extending to small consumers some distance from the main high-tension line is too high and only the larger

consumers, or small ones *en route* between large ones, can profitably be taken in. To reach outlying consumers, Mr. Fennell proposes, as soon as the necessary authority can be obtained, to run an experimental single-phase 3 300-volt single line with earth return. This system, if authorized, will go a long way towards transmitting cheap power to small consumers over widely distributed areas.

Apart from the capital cost of the transmission line, the cost of tapping it for a small amount of power is an important factor, which will have a decided influence on the transmission voltage chosen. It is not economical to build a 33 000-volt transformer for a smaller rating than about 20 kVA single-phase, or 30 kVA three-phase; but at 3 300 volts the limits are about 2 kVA and 3 kVA respectively.

For these smallest economic ratings the equipment (including transformer) for tapping a 33 000-volt line need not cost more than £150 for single-phase and £200 for three-phase, or for a 3 300-volt line £35 for single-phase and £60 for three-phase.

The small outdoor substation can be mounted on a single pole for sizes up to 30 kVA at 3 300 volts; 33 000-volt gear is naturally heavier and requires an auxiliary pole with a wooden platform or, alternatively, a concrete raft, with switches and fuses mounted on a pole.

(II) Standardization.

The second factor on which we need to concentrate in the obtaining of cheap production is standardization; and to effect any influence on national economy the question must be viewed in the broadest sense. A comprehensive scheme of standardization for electrical machinery involves the standardizing of :—

(1) Quality of materials;
(2) Performance of electrical machinery;
(3) System voltages and frequencies and machine ratings; and
(4) Designs.

(1) *Quality of materials.*—The common materials essential to the construction of electrical machinery have to-day reached a uniform standard necessary to the production of competitive products. Every manufacturer purchases such materials as electrical sheet steel, steel castings, copper wires, insulating materials and insulating oil, to a purchasing specification drawn up by himself or jointly with the supplier.

The imposition of special conditions on materials or design may, and often does, act to the detriment of the purchaser of the plant, and the tendency to prescribe such conditions would be obviated if a set of standard purchasing specifications for the principal materials were available. Such specifications should be drawn up jointly by the suppliers and the users of the materials, and they would form the national standards for the industry.

Excellent work has already been done in this direction by the British Engineering Standards Association and the Electrical Research Association, and experience so far shows that those concerned are prepared to abide loyally by such specifications if drawn up on an equitable basis.

(2) *Performance of electrical machinery.*—Standard specifications governing the performance of electrical machinery are in a much more advanced state than those for materials. Thanks to the persistent and untiring work of the B.E.S.A. these specifications are now no longer regarded as the pious opinions of a self-constituted committee, but the generally accepted national standards of reference. We are in sight of the day when long and tedious individual specifications will disappear and machinery will simply be purchased on the basis of the British Standard Specification. The effect of this on the possibilities of highly standardizing the product, and its natural effect in reducing the cost of production, cannot be too strongly insisted upon.

The Verband Deutscher Elektrotechniker Rules in Germany have long been established in this position, and this has been one of the most important causes of the position of Germany in the world's electrical markets.

Of equal importance with the consideration of these matters nationally is their consideration internationally. Standard international specifications will do much to lighten the burden of the British manufacturer in the export market. International standards would put world competition on an equitable basis and effect economy of effort and expense, which could be directed into more profitable channels. The International Electrotechnical Commission is now sitting again regularly and progress in this matter may be hoped for.

(3) *System voltages and frequencies and machine ratings.*—The terrible jungle of voltages and frequencies in this country has been one of the most serious impediments to effective standardization of electrical machinery. Although the efforts of the B.E.S.A. and the authority of the Electricity Commissioners have at last enabled us to see daylight, we are still confronted with 45 different system voltages (excluding low-tension distribution voltages below 600 volts) and 16 different frequencies. It is noteworthy that rather more than one-quarter of the total alternating-current plant installed in this country is for frequencies other than 50 cycles.

These conditions, and the relatively small demand at any one time for quantity orders for any particular system, make it impossible for the manufacturer to stock wound and finished motors, transformers, etc. The advantages of mass production as regards cost, stocking in large quantities and speedy delivery, are out of reach. By way of illustration of what we have to contend with, I recently analysed orders for transformers over a period covering 1 705 transformers manufactured, aggregating 750 000 kVA. For the home market the number of different h.t. voltages was 36, and of l.t. distribution voltages 44. For the export market (covering all parts of the world, except America) the numbers were:—h.t. voltages 46 and l.t. distribution voltages 38. These figures covered a range of voltages as follows:—

	H.T. volts	L.T. volts
Home	2 000 to 66 000	100 to 670
Export	2 000 to 132 000	100 to 600

For the same batch of orders the total number of different kVA ratings was 88 for single-phase trans-

formers and 97 for three-phase transformers, the range of rating covered being

Single-phase ..	..	2 to 7 833 kVA
Three-phase ..	..	1·8 to 12 000 kVA

Had these orders been all for standard voltages such as those recommended in B.S.S. No. 117 and for standard ratings in reasonable, well-defined steps, I estimate that the total saving in cost would have amounted to approximately 15 per cent; and this in spite of the fact that the total kVA supplied would have been appreciably higher, by reason of selecting the nearest standard rating to the one actually specified.

The trouble with electrical machinery is that it is so flexible as regards design. Before standardizing was thought of, the user of electrical machines dropped into the habit of specifying the exact power he thought he required (howbeit this might be incorrect by anything up to 50 per cent), and the manufacturer accommodated one of his already executed sizes accordingly. This flexibility has been a good servant but a tyrannical master.

(4) *Standardization of designs.*—Standardization of designs of the numerous manufacturers is a field which has, as yet, been little explored. Such a proposition is likely to be regarded with suspicion or as outside the range of practical policy. It is, however, quite conceivable that it may become, in the not distant future, a national necessity, to enable this country to hold its place against world competition.

I have already referred to the advantageous competitive position of America and Germany in certain lines of electrical machinery and apparatus. The benefits of quantity production and resulting lower material and labour costs, and the large home demand, enable these countries to undersell Britain.

Particular examples to which this applies are industrial motors and small and medium sizes of distribution transformers. The total annual output of the U.S.A. in industrial motors and transformers is something like 10 times that of Britain; and in face of this we have in this country no less than 80 firms manufacturing industrial motors and 15 firms manufacturing distribution transformers (both these numbers including the large firms who make all sizes).

The position we are faced with is that all these firms carry equipment and staff for handling a great variety of sizes and types, *and none of them are manufacturing in really large quantities.*

If designs could be standardized all round and the industry so organized that work was distributed to the individual firms with reference to their equipment for the most efficient handling of each particular range of sizes and types, great benefits would accrue in cheaper cost, more efficient production, shorter deliveries, reduction in spare parts, and prolongation of life to the harassed designer.

Such a step would not be as revolutionary as might be supposed at first sight. The design and the general construction of the standard types of electrical machinery are nowadays based on certain well-defined and similar lines for all manufacturers. (The dissemination of information through the medium of this Institution has contributed largely to this.) The materials used are practically identical, often being bought from a common source.

The designer's art in standard electrical machinery has reached nearly the top of its saturation curve, as is shown by the fact that weights and efficiencies of machines of different makes are very near to one another. The only differences are in details of construction and dimensions, bound up with the standard sizes of cores and tools which the individual manufacturer has adopted.

Unification of designs would not involve the revelation of any jealously guarded secrets. The designer's art to-day does not involve such issues, but is mainly a matter of designing to fit his particular shop conditions and limitations.

By way of illustration of the gain that could be effected under such a scheme, I estimate that, given sufficient total demand in standard sizes and voltages, distribution transformers up to 1 000 kVA could be produced at from 15 to 20 per cent lower cost. As regards industrial motors, a writer in a recent issue of the *Electrical Review** estimates that a particular size of motor could be turned out at from 20 to 30 per cent less cost.

The conservative and tradition-laden mind will doubtless regard these figures with scepticism and will probably raise such objections as the following:—

(1) The difficulty of distributing the work when there is not enough to go round, or when there is a dearth of orders in any particular range of sizes or types.

(2) There will be less employment for workmen and staff.

(3) Some of the existing plant and tools will be rendered idle in certain firms.

(4) Stagnation in design will set in.

(5) The smaller firms will tend to be exterminated.

Well, difficulties are made to be met, and my reply to these criticisms would be:—

(1) The problem of distribution would be less difficult than the problem every manufacturer is faced with—that of filling his shop under present conditions.

(2) The argument of reduced employment is scarcely worth considering: it was faced, and successfully, when machine tools were introduced to supersede hand labour.

(3) Tools no longer required would be scrapped as, and when, they became obsolete or worn out; the change over would necessarily be a gradual one.

(4) Design would not stagnate—foreign competition would see to this.

(5) The small firm would have additional strength given to its position, as it can often, even under present conditions, produce small machines, in quantity, cheaper than the large firm.

The gist of the matter is that co-operation is more conducive to progress than competition. Rank heresy as this may appear to some, the national aspect must be put before the parochial one. What is needed is to cut out internal national competition and combine the engineering brains and resources of the nation to meet foreign competition. Higher efficiency of production and cheaper costs are, at the moment, vital to the prosperity of the industry and of the community.

* *Electrical Review*, 1925, vol. 17, p. 606.

Registration of Engineers.

By obtaining a Royal Charter this Institution has made a great step towards the realization of the time when all who profess and call themselves engineers must comply with a definite and high standard of qualifications. One step further is, however, essential, namely the registration of engineers by Act of Parliament. The result of registration would be that only registered persons would be permitted the use of the title "Engineer" (or "chartered electrical, civil or mechanical engineer"), and only registered engineers would be recognized by law.

The standard of entry and qualification would be made quite definite, to the benefit of the whole profession as regards the quality and efficiency of engineering work and the status of the technical engineer, and to the benefit of the public in protecting it from unqualified practitioners. It would also aid in dispelling the appalling ignorance of the public regarding a profession on whose efforts it is dependent in one way or another for practically all its conveniences and comforts.

We may then look forward to the time when the public (and the "learned" professions) will have been educated sufficiently to distinguish intelligently between a "chartered electrical engineer" and a "registered plumber and electrician."

What is needed is the setting up of a statutory General Engineering Council (analogous to the General Medical Council) which would determine the standard of training and qualifications required and would keep the register for the profession. Such a body should comprise representatives of all the interests involved, principal among which would be (1) the profession, as represented by this Institution and the other leading engineering and scientific Institutions and the (so-called) protective organizations, such as the Society of Technical Engineers, and the Electrical Power Engineers' Association, (2) the engineering employers, as represented by their leading Associations, (3) the universities and technical colleges, (4) the Government.

As regards the standard of qualification, this should not merely be on the basis of examination or academic degree, but I think the requirements of the Institution for chartered membership are now on such a comprehensive scale that they could be adopted as a basis for registration.

Technical Training.

Closely allied with this subject is that of technical training. The educational training of the technical engineer has now practically become standardized to a technical university course of 3 or 4 years, with 2 years of workshop training either before, after, or sandwiched.

From observation and inquiries made at a number of representative technical universities, I gather that the standard of ability and intelligence of students has somewhat declined since the immediate post-war years, although it is generally higher than the pre-war level. The number of students is on the whole above pre-war, which is only consistent with the development of the industry.

The industry is, however, absorbing all the students who complete their courses of training, so that there is very little competition or room for selection. The industry needs more than ever the best men in order to compete with foreign competitors, whose activities are gaining in strength every year. To maintain and elevate the standard in all grades of technical occupation it is necessary to attract the best type of men and in greater numbers.

Registration of engineers would ultimately conduce to this end, but meanwhile we might, with advantage, concentrate more on the means of selecting and training the best brains from all sources. Scholarships and evening classes are supposed to offer such means, but the available scholarship facilities are inadequate and, without in the least disparaging the extensive and laudable work of the evening technical classes, I am inclined to think that they attempt to carry too great a burden.

Evening classes originated in a movement to give opportunities for artisans to obtain instruction in the scientific principles underlying the manual operations they carried out during the day; and the more technical and scientific knowledge the craftsman has, in his sphere, the better the standard of work. But the evening classes now aim at offering a complete course extending over 5 or 6 years, for apprentices engaged at a works all and every day, as a substitute for the 3 or 4 years' day course open to those more fortunately placed financially. With the enormous amount of ground covered by electrical engineering, and under present-day conditions, this system has become too strenuous mentally and physically to equip and produce finished engineers of the type of which we should wish to see the profession composed.

Here, in Manchester, a start at tackling the problem has been made by one large manufacturing firm, by providing facilities for the most promising apprentices to attend one whole day per week at the College of Technology, thereby reducing the amount of evening work by an equivalent amount. Far-sighted and commendable as this is, it is only a half-way house; the steps I would advocate are:—

(1) To restore the evening classes to their original sphere and encourage artisans and draftsmen to attend courses of specialized instruction;

(2) To provide greater facilities in scholarships for full-day training;

(3) To provide an adequate number of technical schools with a 2-year day course at reasonably low fees (similar to the Continental "Technikum"), for the training of draftsmen, test hands, etc., after or sandwiched in their works apprenticeship.

It is perhaps not generally known that the B.E.A.M.A. have established a number of scholarships in engineering, an example which might well be emulated and extended by other such bodies, as it is doubtless a sound investment for the industry.

Institution Activities.

It is gratifying to note an increase in the number and variety of the papers offered to the Institution, but the number accepted as suitable for reading and discussion is still low. There is, I think, some degree of

reticence in offering short and pithy papers on practical subjects, engendered by the feeling that the voluminous and classical type of paper has become the accepted standard. I think that much would be gained by the reading and discussion of groups of short papers on specific subjects, presented simultaneously by a number of experts in the particular subject.

Another direction in which advantages would accrue is the elimination of overlapping with other Institutions. The mass of meetings of different societies which might be attended by an engineer wishing to keep abreast of progress in all branches with which he is concerned, would easily fill up all his leisure time. The time is over-ripe for an organized system of joint meetings between the leading engineering Institutions and scientific Societies, whereby the efficiency of the whole business may be improved. Many useful joint meetings have been held, but these efforts need to be systematic instead of spasmodic. There are many subjects of common interest, and this course would produce discussions of greater real value and breadth of view.

Another matter to which I suggest the Institution might give its attention is the organization of juvenile lectures on the fundamental ideas of electricity and its applications. One or two lectures each year, by an eminent and popular lecturer, to a large juvenile audience would be of great educational and missionary value; the surest way to get the public mind right as regards electricity is to get hold of the younger generation.

The popular lectures in this Centre have been a marked success, and I think also that we might, with advantage, devote one evening each year to a lecture on the historical side of our faculty. By reason of the enormous ground that has to be covered in the modern university course, this aspect of electrical engineering is crowded out and little appreciated by our younger men; and with the commercializing of electrical engineering the splendid work and tradition of the great pioneers are all too apt to be forgotten. We commemorate each year the work of the great masters, Faraday and Kelvin, and I think that periodic orations, essentially historical and biographical, would stimulate our efforts and keep green in our memory the achievements associated with such names as Volta, Maxwell, Tesla, Hertz, Ayrton, Silvanus Thompson and others to whom we owe our foundation and heritage.

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By S. DERWEN JONES, Member.

(*Address delivered at* LEEDS, *10th November*, 1925.)

It is now six years since the passing of the Electricity (Supply) Act, 1919, which was expected to revolutionize speedily the supply of electricity. We heard a great deal about 16 super-power stations, and great schemes for harnessing the tides so that we should have "a cheap and abundant supply of electricity." Much good work has been accomplished, but progress has been steady rather than phenomenal.

The aim of legislation has been to get unity of control, which necessitated joint working. This could have been effected if the original Bill had been passed, but very conflicting interests have made themselves felt. Only one Joint Board so far has been formed. As the Boards have not compulsory powers, it has not been possible to get the best results. Complaints are sometimes made that municipal electric undertakings are a monopoly, but this is almost of necessity, as with gas and water.

The view is held that to safeguard against monopoly there ought to be representative control, which is the case in municipal work. Unfortunately, in municipal matters there is a great amount of inertia and also a lack of vision and of a bold policy, except in those cases where there is a strong, far-seeing engineer backed up by a sympathetic Council, and especially by an energetic chairman of Committee having business experience.

The weakness in towns making a combined effort to further electricity supply is that there is a lack of driving force. The various Councils keep changing in personnel, their interests are not continuous and consistent, they are wanting in initiative and the Councillors individually lack a direct personal interest. A company has the advantage of a steady, consistent policy from year to year, the administration has a freer hand, and the board of directors have a very strong personal interest in the success of the undertaking. If companies are, however, given monopoly rights they would not be human if they did not take advantage of it; and once fully established in those rights, and with the fear of competition removed, they would tend to cease moving with the times.

Many people who look to a sane individualism to bring Britain into a new era of prosperity would gladly entrust private companies with the supply and main distribution of electricity if they knew that they had a sufficient check upon the companies' operations. They feel that merely to limit the amount of the dividends is not sufficient. Municipalities have to make public all the results of their undertakings, and if companies are given any powers of monopoly their profits would not be grudged if the operation of their undertakings were open to an impartial supervision by keen men of business who had the confidence of the general public.

The Electricity Commissioners in their last Report deprecate the fact that the spirit of the 1919 Act has not been carried out owing to the attitude of authorized undertakers, and that they have been unable in any district to secure a thorough re-organization of electricity on the lines of that Act. They suggest that the whole position requires reviewing; and, if rumour be correct, the Government are bringing forward new proposals to strengthen that Act.

I think the lack of progress has been largely due to two or three causes. In the first place, I consider that a mistake was made in not compensating those authorities whose generating plant was to be closed down, for their outstanding capital account on their generating plant. It can also, I think, be maintained that before any authorized undertaking should be compelled to give up its rights to generate electricity, after having through many years of struggle built up a good load, such undertaking should be guaranteed that the new conditions should not be a little better than the old, but that within a reasonable period it should be at least 15 or 20 per cent better off after surrendering its autonomy.

Again, many of the smaller municipalities would readily take their supply from a larger municipality or from a public representative body, but view with distrust the taking of a supply from companies having a monopoly. In the case of a public representative undertaking, the financial and technical results are available to the public, but this is not the case with companies. It is quite natural that, as business undertakings, they do not care to publish all their results, but they cannot, or should not, have it both ways. If they desire to have a monopoly they should be open to criticism. We are assured that in case of unfair treatment the Commissioners can be appealed to, but however highly the Commissioners may be regarded, both for their knowledge and for their impartiality, an appeal to them or their successors cannot be regarded with as much favour or confidence as the right of the purchaser to buy in the open market in which he has some representation.

Considerable progress has, however, been made since 1919. The total capacity of the generating plant in Great Britain was then about 2 310 000 kW, and in the next two years some 180 000 kW of obsolete and inefficient plant was scrapped. The present total of plant amounts to approximately 4·5 million kW, an increase of 90 per cent. At the same time, whilst in the year 1924 the units increased 16·4 per cent,

the consumption of coal increased 11·2 per cent, and it is significant that this improvement was shared by many comparatively small stations and was not due entirely to the supply from super-stations.

We have heard with wearisome reiteration the parrot cry of "a cheap and abundant supply of electricity" uttered by politicians and the "stunt" Press who have little knowledge of what they are stating. Electricity supply is becoming cheaper and consequently more general, but the time has come when the question of coal, upon which electricity supply so much depends, is of overwhelming importance to the prosperity of our country.

In the last 50 years the output of coal in Great Britain has doubled, but that of America has increased tenfold. In the same time the total world production has increased ten times, but Great Britain's share has fallen from two-thirds to one-fifth of the total production. Many estimates have been given of the life of British coalfields, but it is more important to consider their economic life, and judging by the number of unworked-out pits that have been closed down during the last two or three years, this is a very serious consideration indeed. Many causes have contributed to this, the increasing depths at which they are worked, the thinness of the seams, and the reduced demand for British coal.

We have now to compete in a far greater degree than hitherto against American coal; South Africa now supplies a part of the wants of the southern hemisphere; China has immense coalfields and also cheap labour; and, in Europe, Sweden, Italy and France have tremendously increased their power supplies by the use of hydro-electric undertakings, making them more independent of British coal. France alone has increased her water power since 1914 from 800 000 h.p. to over 2 million h.p. The very economies that are being made in the use of coal at home are in themselves contributory to the depression of our coal trade.

It is said that water and oil will not mix, but they can combine in their effect upon the coal trade. It is computed that oil consumption doubles every 10 years and the world production of oil has reached 120 million tons per annum. Our Navy as well as other Navies once depended upon anthracite coal from South Wales, but are now largely run by oil, and with the improvements in Diesel engines our mercantile marine is gradually turning over to oil and Britain is paying £45 000 000 per annum for oil from abroad. Our first line of defence draws its oil supply largely from Persia, which is too near to Bolshevist Russia for our comfort. A striking instance of the change-over to oil is the case of an American liner which formerly carried 3 000 tons of coal and burnt 300 tons per day and now carries 2 500 tons of oil and burns 250 tons per day, the staff employed with coal being 242 and with oil only 84.

And this depression does not stop at our coal trade, for dear coal means reduced and less economical shipping, dearer transport for our imports, less shipbuilding, and, in its turn, less work for steel furnaces and engineering.

These facts require to be realized not only by the miners, but also by the whole country. The former, despite the slackness with which they are, I think, in many cases rightly charged, are not too highly paid, considering the irksomeness and danger of their work. And I appeal more especially to the whole engineering profession, for it is to our gas, electrical and chemical engineers to whom we must look for a lead, not only in stemming the decline in our country's prosperity but in helping it to take again its due and honourable share in the world's work.

Considerable research and practical work, which bids fair before many years are over to revolutionize the use of coal, has been, and is now being, done on the burning of pulverized fuel and on low-temperature carbonization with the recovery of by-products. Much of this work is being done in America, but it is pleasant to know that successful experimental work is being carried out in Great Britain, and perhaps what may prove to be the most hopeful work in connection with pulverized fuel and low-temperature carbonization is now being carried out by British engineers in America.

In Great Britain, up to quite recently, it has been a commercial proposition to generate electricity only by burning coal in its raw state, but from a national point of view, with the increasing knowledge gained, this is a great waste. The fact that a public-utility concern procures its gasoline to run its omnibuses from the coal which fires its boilers is a good popular lesson against the wastefulness of burning raw coal.

It has been proved that any bituminous coal can be burnt efficiently in the powdered form, even with a very high percentage of ash. There is a large amount of fine coal at the collieries which is expensive to transport, but would be available for use in the pulverized form at a low cost if used on the spot, and would go far to offset the advantage of putting the generating station where water is plentiful for condensing purposes but where coal has to be conveyed at added cost.

It is maintained by some authorities that we cannot get out of coal of low calorific value any more heat by one method than by another. One eminent engineer, however, states that in one plant of which he knows, they burn as many as 25 different kinds of coal in a month, and that when pulverized it can be handled with a precision and uniformity impossible with very dirty coal on chain grates and mechanical stokers; and further, that they are enabled thereby to buy coal to greater advantage in a varied coal market. Banking or stand-by losses are also largely done away with—surely a very important point in a system of interlinked stations, where one or two stations would take up the night or week-end loads.

Despite the fact that coal dust when only partially consumed may become covered with a glaze from the ash, whereby the carbon is not thoroughly burnt and its heating value lost, it is claimed from actual practice that the loss is extremely small when compared with the ash in mechanical stoking; and even when there is a deposit of fine ash on the ground in the neighbourhood it is free from sooty or tarry matter. Great overloads can easily be carried and accurate control maintained to suit all variations of load, and the smoke problem is overcome.

Labour costs are low and it is stated of the boiler-house of the Ford motor works that "eight large boilers are installed, completely operated by two firemen in spotless white suits and seated in front of a control switchboard, cool atmosphere, no speck of dust anywhere, all fittings nickel-plated, floors enamelled and with rubber covered paths."

One advantage of the above method is that the boilers can be fired at the same time with pulverized coal and blast-furnace gas, the top burners taking the pulverized coal and the bottom burners dirty blast-furnace gas. Tar and other fuels, even sawdust, have also been used with the coal.

In the case of the Ford plant at Detroit the normal fuel consumption of the plant of three working boilers is given as approximately 67 million cubic feet of blast-furnace gas and 275 tons of pulverized coal for 24 hours.

Though up to the present mostly operated in America, there are now important plants in operation in England, such as the plant at the Nechells power station of the Birmingham Corporation, and it will be very interesting to watch the progress of these installations.

A very hopeful method is the combination of the production of pulverized coal with low-temperature carbonization. When it is considered that instead of burning raw coal, involving great national waste, it is possible to obtain pulverized fuel giving efficient smokeless combustion, motor spirit, fuel and Diesel oils, sulphate of ammonia and rich gas for power or heating purposes, the overall saving would check the decline in the coal trade, in a more positive manner than dangerous subsidies. Even if the saving did involve by its greater efficiency a reduction in the coal output, the increased national manufacturing and agricultural output would steadily absorb the surplus mining labour, thereby saving the great waste of unemployment pay with its demoralizing effect.

It has been estimated that the raw coal for one 50 000-lb. boiler per annum could produce by low-temperature carbonization 27 500 gallons of motor spirit, 206 250 gallons of oils, and 92 tons of sulphate of ammonia, with the balance of gas and solid fuel for the boiler.

When it is considered how much we spend on imported oil on the one hand, and that we pay £300 000 000 per annum for imported food, is it not time that there should be a more combined effort to check—nay, to stop—this national waste, which we cannot at our peril allow to go on.

Perhaps the most hopeful development in this direction at present is the method adopted in the new McEwen–Runge process of combined pulverization of coal and low-temperature carbonization. Hitherto low-temperature carbonization methods have required a long period for the operation, necessitating the use of small retorts. The coke produced also was too friable, especially for transport. Mr. McEwen has got over this difficulty by dispensing with retorts. The coal, after it is pulverized, is raised to the top of a tower and in falling is met by a current of hot inert gases. By this method carbonization is effected by the time it reaches the bottom of the tower, the process being very simple. The volatile gases pass out at the top and the finely divided coke passes out at the bottom to be fed to the boiler in the same manner as pulverized fuel. The method is being put into operation at the Lakeside power station, Milwaukee, and it is claimed for it that the powdered semi-coke is superior to pulverized fuel for boiler furnaces. It can easily be transported and also pumped through pipes like oil. High claims are made for the quantity of tar per ton of coal and for the heating value of the gas, the latter figure being 750 B.Th.U. per cubic foot.

This powdered coke will be of no use for the domestic hearth, but the Glasgow Corporation are, from the account of Councillor Smith, Convener of the Glasgow Health Committee, given at the Royal Sanitary Institute Congress at Edinburgh, doing good work in that direction. After long experiments on a smaller scale, a large plant at the Dalmarnock gas-works for the low carbonization of coal has been installed, and they have succeeded in producing :—

(*a*) Smokeless fuel that will burn in any type of grate as easily as raw coal, and as cheap as raw coal under equal conditions ;

(*b*) Gas suitable for industrial purposes.

The capital and working costs are low, and from tests made, taking coal at 20s. per ton, excluding the cost of handling, the price of gas would be about 1·01d. per therm.

Councillor Smith states that they hope to carbonize 500 000 tons of coal per annum, from which, in addition to the gas obtained, they would produce 275 000 tons of smokeless fuel for domestic purposes and 7 800 000 gallons of oil.

Many electrical engineers are hopeful of the coming of all-electric houses, with the saving clause that one room will have a grate for burning smokeless coal or coalite ; and in Glasgow I understand that they are taking very successful steps to electrify workmen's cottages, in which all the water-heating is done with a small coal or coke stove. I venture to suggest, however, that fires, either coal or gas, could be abolished from the houses. It seems to me that up to the present only the middle and upper classes have, in the main, had the advantages of electricity supply. In Glasgow, out of 200 000 houses, only 9 per cent have electricity installed, and by far the greater proportion of this percentage belongs to people comparatively well off. In all our large towns there are thousands of houses—one can hardly call them homes—which an enlightened community should not tolerate. Without going into the question as to who are, or what is, responsible for the existence of these dreary regions where the sunshine only makes more apparent the drabness of it all, I venture to suggest that there is a way to make a clean, healthy neighbourhood where there is now only squalor and dirt. I do not think it can be gainsaid that smoke from domestic fires is responsible for half the pollution of the atmosphere ; and over 5 per cent of the coal so burned escapes into the air.

Many will remember the clearness of the air during the last coal strike, and in the Batley area during the

late strike in the woollen trade the towns seemed transformed, even ugly buildings seeming less repellent, and one breathed a purer, serener air. This is no mere matter of sentiment. As Dr. Vernon Sinclair has stated in the *Electrical Review*, speaking of " Combustion and Atmosphere and Their Relation to Disease " :—

" Heating in greenhouses is always so arranged that no products of combustion enter the greenhouse, because every gardener knows that the plants wither and die if they are given air to breathe which is impregnated with gas and coke combustion products."

He further condemns heating and cooking by gas in houses because of the formation of carbon monoxide. Is it any wonder that a C3 population grows up in the congested area of our towns? And it must be remembered that it is just in these areas that there is by far the greatest proportional increase of our population. The doctors further inform us that the clouds which form round the dust particles of our northern manufacturing towns, creating our muggy depressing atmosphere, also prevent the most health-giving portion of the sun's rays reaching us.

I have laboured the effect of our smoke-laden atmosphere on the general health of the people, but I hardly think that it is necessary to point out to engineers the enormous cost of this pollution, both in labour and in material, which it would be difficult to estimate, and the prevention of which would release a great source of wealth that could be used in more remunerative ways, not to mention the great increase in the means of leisure and the joy of life.

I think that the time has come when electricity and gas should combine their forces and endeavour to do away with this great evil. I was greatly pleased when our Past-President, Mr. Woodhouse, spoke of the need of co-operation between gas and electricity, and I hope that steps will be taken before long by our Institution towards that end. Let us have a keen friendly rivalry by all means, but it must not be forgotten that as electricity has progressed, gas has also, and will continue to do so, though no doubt along new lines.

One way of cleansing our slums is on the lines now being experimentally carried out in Glasgow, Woolwich, Gateshead and, in the near future, Leeds. I refer to the construction of all-electric houses, and in this work Glasgow is contributing, by producing " coalite " for burning in domestic hearths. With the experience gained, however, I think that there is a need for bold schemes to be initiated in order to ensure success. To this end I venture to suggest that gas could largely contribute. But I would keep gas outside all premises. Let the houses be all-electric, with no coal fires. The general heating of the houses, I think, could be done by hot-water radiators.

From the curves given in Technical Paper No. 12 of the Fuel Research Board, on the heating of rooms, Dr. Margaret Fishenden shows that hot-water radiation is the cheapest form of heating rooms of about 1 000 cubic feet capacity, i.e. the size of rooms in the type of house we are considering. Would it not be possible to build these houses in blocks of, say, 20 or more, with a common hot-water supply at a temperature suitable for warming the rooms, and supply all requirements for baths and general washing and cleaning? All hot water for drinking purposes would, however, be electrically heated, as the main hot-water supply would not be suitable for that purpose. The hot water would not be metered, but there would be a general supervision to prevent waste in the same manner as is now done in some cases where electricity is supplied on the current-limiter system. I think that the whole matter would become normal as the users became educated to the advantages and realized that waste would be injurious to their best interests. The cooking, lighting and occasional use of an electric radiator in any room to supplement the hot-water radiation would give a large electric load with a good diversity factor.

The water for the hot-water radiators could be heated by gas in a small building near the houses and thermostatically controlled. Gas for this purpose could be distributed in specially laid mains, and at a cheaper rate than that now supplied for gas lighting. According to an eminent gas engineer, Mr. George Helps, Leeds was offered a supply of gas from collieries at 7d. per 1 000 cubic feet, or under 1½d. per therm; and Sheffield is buying gas at 4½d. per therm, i.e. cheaper than she can produce it herself. Glasgow, as already pointed out, can, by the McLaurin process, produce gas for 1·01d. per therm. Mr. Finn, manager of Manvers Mains coke ovens, has stated in a paper read before the Society of Chemical Industry, at their meeting in Leeds last July, that gas could be supplied from coke ovens at a much lower rate than it is now supplied by gas-works of a standard type, and that it could be carried considerable distances, natural gas having been pumped as far as 200 miles. He also makes the suggestion that gas could be conveyed from the coal-fields to the towns by means of pipes along the railways.

As there would be no ashes from coal fires in the houses, there would only be the ordinary refuse to deal with, and provision could be made for this by having in the building for the gas boiler a gas incinerator, to which all the refuse in that block of houses could be brought, thereby doing away with the unsightly refuse bins and lessening the great cost of refuse collection and destruction. It will be maintained that the householders would not look after the gas-burners, but if there were a considerable colony of such houses it would pay the authorities to employ a man to go round the district for this work, and with moderate care the refuse not only could be burnt without causing a nuisance, but in burning could contribute towards the heating of the water. There would be considerable saving in the building of such houses, in one town such saving on the building of electric houses being estimated at between £30 and £40 per house, and the comparative capital costs of electric mains would be much less because of the density of the area of supply, and the gas mains would also be shorter and simpler.

Among other improvements in the generation of electricity is the use of preheating of flue gases, as exemplified in the Howden-Ljungström air preheater, by which very considerable economies are made in steam-raising. The preheater takes up about 60 per

cent of the available heat in the flue gases, which would otherwise be lost. With the balanced draught used in this method air leakages are very much lessened and the whole working is under easy control.

The revision of qualifications for entry into the Institution is now under consideration. With the greatly increased responsibility of electrical engineers to-day, and the wide scope of their work, it follows naturally that our Institution, with its growing prestige, should demand a higher standard of entrance into its ranks. It is not always easy to define what constitutes a competent engineer. Some year or two ago the Electrical Power Engineers' Association issued a report which gave in a very able manner the requirements in the training of electrical power engineers.

Many of the large electrical engineering firms have an excellent system for the training of young engineers, and, now that generating stations and transmission systems are developing on such a large scale, it should be possible to give not only a thorough training to the young engineer in his particular department, but also, if he shows special ability and industry, the opportunity of obtaining a larger knowledge of the undertaking in its various branches.

I think, however, that in the training of youths to-day there is a danger of too great a diffuseness, and their knowledge is not sufficiently in touch with the facts of life. Professor Perry laid great stress on the need for experimental work and a quantitative grasp of the subjects which the student has learned from books. There is no doubt that the familiar handling of an object leaves a firmer impression on the mind than any amount of description of it. The present-day youth has a very keen insight into many mechanical problems, from the upkeep of his motor-cycle or car, and as for electrical knowledge, the young wireless enthusiast is wonderfully versed in the intricacies of his subject.

A striking illustration of practice preceding theory is to be found in the very interesting book of Henry Ford entitled "Story of my Life." At his works he started a trade school in 1916 for boys between 12 and 18 years of age who leave school early, and it followed these lines:

The boy is to be kept a boy;
The academic training is to go hand in hand with industrial instruction;
The boy is set to work on articles which are afterwards to be used.
One week is spent in class, then two in the shops, and the teachers are the works staff.

Geography is taught from the shop orders and the handling of goods to all parts of the world. Physics and chemical laboratories are in direct contact with shop practice. On the school machines boys work solely on articles needed by the works, and the articles are purchased by the company; if turned out badly the loss is borne by the school. The school started with two boys and has now expanded to 700 scholars; and an important point, in my opinion, is that it pays its way.

It was stated recently in the electrical Press that there is no public monument to Faraday in our country. This being the centenary of his discovery of benzine. it would be fitting that there should be some tangible memorial of him.

The feeling has often been expressed amongst us that it is desirable that there should be a closer bond between the various engineering societies in Yorkshire. A step has already been taken in that direction by the joint meetings which have been held, but I venture to suggest that the bond can be drawn still closer.

The University of Leeds is now appealing for funds to enlarge its borders. Would it not be possible for the Institutions of Civil, Mechanical and Electrical Engineers to combine and have a joint meeting-place under the wing of the University, and to use a scientific and engineering library instituted there? This would require a generous contribution towards the needs of the University, but a joint meeting-place and library devoted to the advancement of science in the service of man would be a happy memorial to one who devoted his whole life to the cause of science and the service of his fellows.

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By Professor MAGNUS MACLEAN, M.A., D.Sc., LL.D., Member.

"THE EARLY HISTORY OF THE GLASGOW LOCAL SECTION (NOW SCOTTISH CENTRE)."

(*Address delivered at* GLASGOW, 10*th November*, 1925.)

With your good will on this semi-jubilee occasion, I am privileged to be your Chairman. The chief reason assigned, I understand, has been that I was in at the start and largely instrumental in getting our Local Centre formed.

I do not deny the soft impeachment, that I was a prime mover in the matter. On the contrary, I glory in it. All the more, therefore, do I appreciate and thank you for the high honour you have conferred on me in making me your Chairman for a second time. Such recognition I value more than I need express.

It is unnecessary to say that I was not alone in the initial endeavour. There were other ardent coadjutors, though they have not all survived to this day.

In looking over the Minutes of Committee and General Meetings, as well as of the Students' Section, it has occurred to me that from these, and Press and personal recollections, it might be interesting to give on this occasion a short account of the earlier history of the Centre.

Prior to its inception, towards the end of 1899, the late Mr. Henry Mavor and I drew up a petition to the parent Institution in London, which was circulated among the resident members and signed by them, stating cogent reasons why we should be allowed to form a Local Section, and the sanction of the Council was obtained on the 14th December in that same year.

It was on the evening of Thursday, the 18th January, 1900, that a meeting of the electrical engineers resident in Glasgow and the West of Scotland took place at 207, Bath-street, to form a Glasgow Local Section of the Institution. At this meeting, Prof. Perry, the senior Vice-President of the Institution, presided, Mr. McMillan, the Secretary, also being present. Prof. Perry gave an interesting and entertaining address on the objects and work of the Institution, and Mr. McMillan some explanations regarding the working of Local Sections. Lord Kelvin was unanimously elected first President (we say Chairman now). For the other offices, there were several nominations, and, after a vote, the following were declared the successful nominees :—

Vice-President: Prof. Magnus Maclean ;

Hon. Secretary: Prof. W. H. Watkinson ;

Members of Committee: W. A. Chamen, H. A. Mavor, W. W. Lackie, W. B. Sayers, Thomas Young, J. M. M. Munro, Prof. Andrew Jamieson, and Francis Teague.

At the first Ordinary Meeting in February, 1900, in the old Technical College, Bath-street, a paper was read by Mr. W. B. Sayers on the "Problem of Arc Lighting from 250-volt Supply." At the next, it was announced that no lengthy reports of the proceedings of the Section should be communicated by anyone to the electrical or other journals until the decision of the Council of the Institution as to the propriety of such publication had been received by the Section. Mr. W. W. Lackie contributed a paper on "Methods of Charging for Public Supply of Electricity," the subsequent discussion proving very lively and vigorous.

After the third meeting, at which the annual business was transacted, the meetings were transferred to 207, Bath-street.

The Minutes of the first Ordinary General Meeting of the Section held on Wednesday, 14th November, 1900, at 8 o'clock in the rooms, 207, Bath-street, show that the President, Lord Kelvin, was supported on the platform by the Vice-President, Bailie Maclay, Convener of the Glasgow Electricity Committee, and the paper was given by Mr. W. A. Chamen, on "Electrical Supply." This was the only meeting at which Lord Kelvin presided during his term of office. I had the honour of acting in that capacity from the 16th February, 1900, until the seventh Ordinary meeting of the Session 1901–2, held on the 13th May, 1902, when as Chairman, the title then adopted, I was succeeded by Mr. Henry Mavor. During that session 11 Members, 16 Associate Members, 20 Associates and 7 Students were added to our number. Our Section had the distinction of being the first and only one up to that date to secure an Institution Premium, awarded to Mr. A. B. Field for his paper on "A Method of Compensating Voltmeters for the Voltage Drop in Long Feeders." Another Premium was awarded to the same member in 1903 for his paper on "A Study of the Phenomena of Resonance in Electric Circuits by the Aid of Oscillograms."

The Committee Meetings at that time were mainly devoted to discussions on (1) the grants to Local Sections for expenses, and (2) the area of the Glasgow Local Section. In connection with (1) it is interesting to quote from the minutes of the 17th September, 1900. The Hon. Secretary stated that at present the funds of the Local Section were lodged in the bank in his own name only, and requested that a second name should be added. On the proposal of Mr. W. A. Chamen, seconded by Mr. Thomas Young, I was requested to act with the Hon. Secretary. From that date to the present day I have signed every cheque issued for payment of local accounts. At the same meeting of the Committee, the Hon. Secretary stated that he had received the promise

of seven papers, so that he had been able to fill the whole of the dates. Contrast that with the present method of getting all the papers from London! Last session one of these papers was actually read at 11 different places on 11 different dates. The controversy between the parent Institution and the Local Sections on the proposals that papers should be submitted to the Papers and Editing Committee in London before being put down for reading at the Local Section is now a thing of the past, so, although they are all very interesting, I shall not quote any extracts except this one from the minutes of the 9th September, 1907: "There was considerable discussion as to the action this Section should take, and it was finally decided that in view of the undoubted unworkable nature of the arrangement, this Section should take a somewhat passive attitude, and let the scheme become a dead letter by inaction." Later on we find that our Hon. Secretary was instructed to write to the parent Institution calling attention to the great inconvenience caused by the delay in dealing with papers submitted to our Section.

Early in 1901 the Committee were asked by the parent Institution to state the area that they considered should be allotted to the Local Section, and, after considerable discusssion, it was left to me to discuss the matter with Mr. McMillan in London and put forward the best proposals which he considered would be acceptable. At that time, the members of all grades resident in Glasgow were 104, and 15 outside the city had specially asked to be enrolled as members. Thus, out of 142 connected with the Institution who were resident in Scotland, 119 were members of this Centre. Now we have 676 as follows:—

Members	98
Associate Members	280
Graduates	93
Students	182
Associates	23
	676

It was in April, 1903, that Mr. F. F. Pickstone brought up the question of the possibility of having meetings in Edinburgh, and suggested that every third meeting should be held in that city. It was pointed out that the question of including Edinburgh within the Glasgow area had already been brought before the Council in London, when our Section had suggested that Edinburgh members should be represented on the Council, and that the meetings in each place should be in proportion to the total number of members in the respective areas. The Council had, however, declined to fall in with the proposal and had definitely excluded Edinburgh from the area of this Section. Mr. Pickstone was informed that the best course to adopt was to get up a memorial from the Edinburgh members, pointing out that they were not strong enough to run a separate Section, and petitioning that they be included in the Glasgow Section. The Hon. Secretary was instructed to receive the memorial (which should be as largely signed as possible) and should pass it on to London, asking the Council to reconsider the matter. Accordingly we find that the Hon. Secretary submitted a letter from Prof. Baily enclosing a draft application which the Edinburgh members proposed to present to London, asking that they should be incorporated in the Glasgow Local Section. The Committee instructed the Hon. Secretary to write to Prof. Baily and say that they quite approved of the form of application proposed. The first formal meeting in Edinburgh under the new arrangements took place on the 19th December, 1911, at the Heriot Watt College.

A reference to a proposed Students' Section occurs in November, 1905. The Secretary brought forward this subject in view of remarks made by Mr. Gray, President of the Institution, at our local Dinner. There was some discussion, after which it was left to the Hon. Secretary to consult with me as to what could be done in this direction, because anything of the kind would necessarily draw the chief support from the Technical College. A minute of the 13th March, 1906, contains a long account of a special meeting held on the 16th February, and a Report from myself as Chairman of the Students' Section giving details of another meeting held by them on the 2nd March and the draft rules adopted, a copy being submitted.

The first meeting of the Students' Section was held in October, 1906, in the Electrical Theatre of the Technical College, when I, as Chairman, gave an address upon the subject of "Electrical Wave Measurements." In the following years I gave lectures on "Testing of Transformers," "The Distribution of Electrical Energy," and "Electric Clocks." The summary of the latter, as given in the minutes, reads as follows:—

> "Electric clocks dated only from the middle of last century. Hundreds of patents were taken out during that time, and of these more than 90 per cent had been failures, owing chiefly to the faulty mechanical method in which electricity was applied. A few of the successful inventions were described in detail and classified under three heads, namely, first, independent clocks which were wound up electrically at regular intervals: second, a number of such clocks which were synchronized electrically by a master clock every hour: third, a number of clock dials which were controlled and impelled by a master clock every half-minute or minute."

For a municipal time service, with dials rented by the public, it was suggested as a feasible system one under which a single master clock, regulated to keep correct time in the usual way, would be able to synchronize every hour a few score of independent clocks situated in different parts of the city. Each of these synchronized clocks could control and impel 200 or more dials in blocks of buildings in the neighbourhood. All the circuits could be put on to the city electric mains, and the total electrical energy would be a few watt-hours per dial per annum.

As an instance of the vigour displayed in the Students' Section, the following were papers read in one evening:—"The Uses of Inductances for the purpose of limiting Short-circuit Currents in Alternators," by Mr. Archibald Page; "Is Switch Control fully taken advantage of?" by Mr. R. B. Mitchell; "Public and Private Supply,"

by Mr. H. A. Stewart; and "Petrol and Electric Vehicles," by Mr. E. G. Bowers.

The Annual General Meeting of the Students' Section for 1913-14 took place on the 3rd March, after which, owing to the war, there was no other meeting of any kind for five and a half years, the first of the ninth session being held on the 14th November, 1919.

With reference to the proposal to Lord Kelvin to take the chair for the session 1906-07, in view of the visit of foreign societies to Glasgow, the Hon. Secretary stated that he was very pleased indeed to announce that he had received a most charming and courteous reply from Lord Kelvin as follows:—

"*January* 24, 1906.

"DEAR MR. TIDD,

"I thank you very much for your most kind letter of January 19, and I beg that you will thank on my account the Glasgow Section of the Institution of Electrical Engineers for their kindness in asking me to be again their President, and to take part accordingly in the reception of the Foreign Visitors on the 2nd and 3rd July. I am afraid I could but very imperfectly fulfil the duties of President for the Ordinary Meetings, as I shall be living in London most of the time from near the end of February till midsummer or later. But I would come to Glasgow for a few days in the beginning of July gladly to be with you all, and to help in receiving our foreign friends, if, in the circumstances, I may be allowed to have the honour of being President of the Glasgow Section."

Another letter from Lord Kelvin, read on the 12th February, 1907, is of great interest now. "I have not been very well since I returned from Edinburgh. I have had a rather bad attack of my twenty-three year old trouble, No. 5 nerve, and I shall be obliged to keep very quiet for some time. I hope next session I may be able to offer a short communication to the Glasgow Section. I am very sorry not to be able to do so at present."

Lord Kelvin died that year, and the short communication offered was never given.

Discussions of the papers were eagerly taken part in during the early years of the Section, a common remark in the minutes being:—"Owing to the lateness of the hour and the interest displayed in the paper, the discussion was adjourned to the next meeting."

The minutes of September, 1903, report this pleasing social innovation:—"In view of the fact that both last session's smoking concert and the previous session's dinner were in their respective ways pronounced successes, and that some members favoured the one form of entertainment, and some the other, it was decided that an attempt should be made this time to meet the wishes of all by holding a dinner early in November to open the session, and a smoking concert later, in February."

I may be allowed here to mention the *Scottish Electrician*, a journal which fought for existence from February, 1901, to December, 1904, 44 parts in all being issued. It contained very full accounts of the proceedings at the meetings during these years, and of our first Annual Dinner, which was held in the Windsor Hotel in this city on Tuesday, the 18th February, 1902, when I had the honour to preside.

In connection with the function, an interesting novelty was introduced which caused, at the time, considerable curiosity and speculation. Attached to the lighting brackets round the room, and hidden by greenery, were arranged a number of loud-speakers, each of which was connected to a transmitter in a room of the Corporation Telephone Exchange in Renfield-street, about half a mile from the hotel, where a small band of wind instruments with a piano was stationed to render a selection of combined numbers and solos, as well as the accompaniments in connection with the loyal toasts, all of which were transmitted over the wires and heard in the dining-hall with a clearness and distinctness thought remarkable and generally commented on.

Even more memorable and interesting than the first was our fifth Annual Dinner, held in the Grosvenor on the 27th November, 1906. The Rt. Hon. Lord Kelvin, Chairman of the Section, presided. Prof. Jack, in proposing the toast of the "Glasgow Local Section," paid a high tribute to Lord Kelvin's standing in the scientific world. He imagined that the verdict of the world upon Lord Kelvin was reasonably and impartially expressed by the deputation of foreign engineers who came to Glasgow, when the Italian delegates brought Lord Kelvin two magnificent volumes containing records of the work which had been recently discovered in Milan of one of the greatest Italians, Leonardo da Vinci—a man whose genius in science was only equalled by his genius in painting and music; one of the greatest men of the world. His books are full of personal notes and drawings done by his own hand, and the Italian delegates felt that there was no place in the world where the works would be more sure of an understanding reception than by bringing them to Lord Kelvin.

Lord Kelvin, who was loudly cheered, on rising to respond to the toast, said that he had listened with intense interest to what had fallen from Prof. Jack. The latter's kind references to himself from the time he entered the University as a child, until to-day, a period of 70 years, from the time he was an inhabitant of the old College of Glasgow, living in his father's house, his father being then professor of mathematics in the University—these references had deeply interested him. He thanked Prof. Jack for the kindliness with which he had spoken of him and for the over-appreciation—he felt it to be more than he deserved—which had been expressed of his scientific work. Prof. Jack had spoken of the constitution of the universe. Electrical engineers knew that their everyday business was the practical applications of science, but they were all scientific men and would sympathize with every application of their science to extend human thought through the remotest parts of the universe, to think of every possible development of dynamic action. To speak only of dead matter—the material subject of an electrical engineer's work—he was sure they were all scientific enough to take an interest in abstract speculations, even to think of the formation of concrete matter from atomic origin. That did not sound very practical; it was not very like the daily business of an electrical engineer, but electrical

engineers were scientific men, and scientific men could not help going beyond their daily range. He was sure they had listened to what Prof. Jack had said, and he was sure they would sympathize with the endeavour of any of their number who went beyond the range of practical science—and tried to penetrate into the secrets of nature, into the works before us, the grand works of the stars and of the universe. One of our greatest electrical engineers, Sir William Siemens, showed that —he (Lord Kelvin) did not say he could lift his mind—he was elevated by his mind from his daily practical work into grand speculations far beyond anything that this world could show of the properties of matter. He (Lord Kelvin) felt that he was there not in the capacity of trying to push farther and farther into endless space the result of dynamic laws, but to represent the Glasgow branch of the Institution. In their name he thanked Prof. Jack, and he thanked all the gentlemen present for the enthusiasm with which they had drunk the toast. It was the toast of "Ourselves" to a large degree, but they had friends among them—they had Dr. Glazebrook and other members of the parent Society.

The Glasgow branch of the Institution was certainly a very large province. Dr. Glazebrook had spoken of the time when there was no Institution of Electrical Engineers, but when there was a Society of Telegraph Engineers. It was considered at that time that the word "engineer" was scarcely touched by the delicate apparatus of the electric telegraph. They had not heard watch-makers called engineers, but they had watch-makers and workers in that domain, such as Wheatstone, whose prodigious practical knowledge of dynamics led him to see in the small mechanism of a watch the means of bringing out electrical results, such as the tremendous result that he gave us of 250 words per minute of telegraphy. That and submarine telegraphy constituted the subject matter and engaged the ideas of persons connected with electric telegraphy. He thought Sir William Siemens was the first to give them the name of "engineers." Sir William Siemens was certainly the founder—he believed he was right in that—of the Society of Telegraph Engineers, which soon after became the Institution of Electrical Engineers. He remembered particularly how they first heard of very large things proceeding from telegraphic work. They first heard of things large really from Siemens. He did not say that there were not others. There was Jacobi of St. Petersburg, who had an electric boat driven by an electro-magnetic engine before the time of Sir William Siemens. That, perhaps, was the first piece of real electrical engineering in the ordinary understanding of the word "engineer"—the applying of electricity to large forces for the benefit of mankind. He still remembered Sir William Siemens bringing before the Institution—he thought it then was of Telegraph Engineers—the means of developing forces at a distance of 10, 20 and 30 miles from the coal-burning to give the forces by a steam engine. The transmission of forces was, he believed, really due—he meant practically the first inception of the idea and the first bringing of it to a practical conclusion or to an advance towards practical conclusion—to Sir William Siemens. He remembered Sir William telling him of work done in the factory of Greenwich in which they had extraordinary tantrums, if he might use the expression, performed by the dynamos that they then had. All present would know what he meant when he said that the dynamos they then had were single-series dynamos. They knew what sort of thing that was if used as a generator to charge a battery, or even to drive a motor at a distance. Sir William and those who worked with him devised the shunt dynamo, and he told them he had made one which had got over all their troubles; but his people were still so averse to it—his people at the factory—that he could not get them to make another. He did not say he could not, but there was great difficulty in getting them to look at such a new thing. He (Lord Kelvin) begged Sir William to make one for him. He did so, and during six or eight years at least it was working in a little room adjoining the physical laboratory of the University of Glasgow. It was driven by a Clerk gas engine, which did its work well. He believed that really the first thorough practical electric lighting that was done anywhere, was done by this Clerk engine and Siemens shunt-wound dynamo. He believed that the first house on this planet in which the whole lighting was done by electricity was a house in the University of Glasgow, getting the current from that Siemens dynamo and the Clerk gas engine of which he had spoken. In that house the rule given to the workers for making what began to be called an installation soon after was: "Go through the whole house, wherever there is a gas burner, put in an electric light." There were 106 gas burners and there were 106 electric lights in that house about the end of the year 1881. There had been houses lighted in London. In Mr. Spottiswoode's (then the President of the Royal Society) there were six electric lights—six Swan electric lights shown and used in one room in the house. Edison had lighted rooms in houses in America. He had never heard that any house was wholly lighted by electric light at that time. There might have been one in America. There was not in this island, he believed. Well, that was a beginning. It was quickly followed by a large spreading out of the electric light. But he felt that the University of Glasgow might look upon it with some interest that a house in the University had its whole electric lighting done in the way he explained. It was not lighted the whole 24 hours. A little before midnight every night he himself used to go across to his laboratory and stop the gas engine, and anyone that wanted light in the house must have a candle, because the gas had been cut off and soldered up. But a little later came the storage battery, and for one whole year in the house there was not an inch of candle burnt. There was no other light—there might possibly have been a cigar light—but that was the very most—that was not done by electric lamps of Swan and Edison. In closing, his Lordship briefly referred to the progress of electrical engineering. From 1875 to 1905 there had been prodigious development of activity in the applications of science for the good of mankind.

I am sure you will agree that this is a most characteristic utterance of Lord Kelvin, and well worth quoting *in extenso*. It shows the great scientist and electrical engineer thinking, on his feet, in his own peculiar style of eager delivery, giving the impression of "thoughts

that broke through language and escaped "—luminous to those who had sufficient knowledge, but deeply involved, discursive and pointless to those who had not; lighting up new fields of thought and inquiry to the more enlightened, but darkening counsel with knowledge to all the *non-parati*. That itself was a thought of wonderful import thrown off in the going-by when in speaking of Sir William Siemens he remarked: " He (that is Lord Kelvin) did not say he could *lift* his mind—he was *elevated* by his mind from his daily practical work into grand speculations beyond anything that this world could show of the properties of matter."

Then there is the marvellous picture in that short sketch of his own house on Gilmorehill, lit by electricity —the whole house—the first on this planet to be so illuminated so far as he knew. He was elevated in his mind to see this advance and how to make it an accomplished fact before anyone else had reached it. Men will go far out of their way to visit old castles and derelict ruins on the Continent, but how many of the citizens of Glasgow know, or in passing look up in wistful cogitation at, this great sequestered edifice. But lo! the scene changes. The magician shows us the same house after midnight lit only by a candle in one room. The previous rustle of a ghostly figure scuttling across the quadrangle in the silence of the night, entering the laboratory, stopping a gas engine, and soldering a pipe in a weird dim red light, calls up visions of Faust and mediaeval wizardry. The man of science by these acts had put back the clock of the ages, but all the time in his quadrangular stride he was searching in his mind for a storage battery.

" Well, that was a beginning," were his own significant words. And he felt that the University of Glasgow might look upon it with some interest. But we, too, as the Scottish Centre of the Institution of Electrical Engineers, can also claim some of the credit and kudos of this great enterprise. He was one of us.

I think it would be a most interesting thing if one of our younger members would sketch the achievements of men of our own Centre along the lines of advance in electrical engineering within the last quarter of a century, the conclusion of which we are now celebrating.

Lord Kelvin's reference at the close of his speech to the progress of electrical engineering suggests an advance since then that not even he could anticipate. " From 1875 to 1905," he said, " there had been prodigious development of activity in the applications of science for the good of mankind." But that was before the development of aeroplanes, and airships, of telephony, wireless broadcasting, heating and lighting in their latest phases. And with regard to the structure of the universe in which he was deeply interested, and to which he made reference, that was before the special and general theories of Einstein, and the new conceptions of the atom as conceived by Rutherford, Bohr, Sommerfeld, and all the rest. How the mind of our late doyen and prince of science would revel in these!

The thought of it all makes one feel that we have now more need than ever for our Local Centre. It seems to stand to us for so much, rendering, in fact, a threefold service. It stands for common social intercourse at our Meetings, and Dinners. As iron sharpeneth iron, so does the face of a man's friend.

It stands for a common interest—electrical engineering with which we are all associated. But—perhaps the most important of all in these times—it stands for a common pursuit. We come here to discuss the science and art of our profession—the rapidly unfolding applications of electricity, and to endeavour to make our knowledge as practically available as possible for the good of mankind. What the next 25 years have in store in this direction, no one can even guess. Electrical engineers may be on the roof of the world, or they may be fitting abodes and means of transport in its interior. At any rate they may be depended upon to give us light and warmth and transport with a few more of the luxuries which science continues to offer.

EAST MIDLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By B. ADAIR M. BOYCE, Associate Member.

"ENERGY."

(Address delivered at LOUGHBOROUGH, *6th October,* 1925.)

I have chosen for the subject of my address this evening "Energy." It is a very old subject and a lot has been written about it from time to time, and from various standpoints; but the point of view I wish to stress in these remarks is the comparatively inefficient use we make of energy. Whilst some of the factors affecting this inefficient use are capable of control, many—without some epoch-making discovery—are not.

Energy may be defined as the "capacity for doing work"; it is the basis of life; and without energy we cannot conceive the existence of any universe. The primary source of all our energy is the sun, but there is also the mechanical energy stored in the rotation of the earth on its axis, heat energy in the interior of the earth, and radioactive substances. Ultimately these can all be attributed to the sun.

The different forms of energy as related to these sources are:—

The Sun.
- Direct radiation. Heat and light.
- Plant life.
- Fuel. Coal, oil, gas, etc.
- Muscular energy. Man and animal.
- Flowing water.
- Wind (in part).

Earth's Rotation.
- Tides.
- Wind and waves (in part).

Internal Heat of the Earth.
- Volcanoes.
- Hot springs and geysers.

Radioactivity.
- Radium.

Before discussing these various forms of energy in detail, perhaps I should state that energy may be divided into two classes, viz.—

Potential energy, or the energy a system possesses by virtue of the position of its parts; and

Kinetic energy, or available energy possessed by a system in virtue of the motion of its parts.

The sun.—The energy received by the earth exposed perpendicularly to the sun's rays at the mean distance of the sun is 2·1 calories per minute per cm^2. This equals 1·47 kW per (metre)^2, or 1·7 horse-power per square yard.

The earth rotates at a velocity of about 17·36 miles a minute at the equator, and the energy stored up by rotation amounts to 10^{25} h.p.-hours, its orbital energy being about 10^{27} h.p.-hours. If it were possible to increase the length of the day by only 5 minutes—by decreasing the rotation of the earth—the stored energy released would amount to 1 000 million h.p. for 70 000 years. Unfortunately, from one point of view, we cannot control this.

Further classifications of energy are:—

Mechanical, Electrical, Chemical,

and also, to the extent to which the various forms are used,

Fuel, Flowing water, Winds, Tides, Ocean waves, Solar radiation, Muscular energy.

Fuel.—The most important form of energy is fuel, comprising coal, oil, gas, wood, alcohol, etc.

The heat value of an average coal may be 11 000 B.Th.U. per lb. Consider how this is used in a modern medium-sized station and let us call the heat in the coal 100 per cent.

We get only 15 per cent out as available electrical energy. We lose 20 per cent in boilers, 1·25 per cent in steam-pipe radiation, 1·15 per cent in turbine and alternator losses, and 61·6 per cent is thrown away in the condenser cooling-water.

While I am on the subject of coal as a fuel, a few figures may be of interest. In 1922 the total quantity of coal raised in Great Britain was 249·6 million tons. Of this 25·7 per cent was exported and only 2·7 per cent was used in electrical generating stations. Domestic fuel accounted for 15·2 per cent—this is probably the most inefficient way of using coal. Gas-works used 6·6 per cent; railway locomotives 5·1 per cent; collieries, for engine fuel, 6·5 per cent; and miners' coal 2·3 per cent. Coal carbonized in coke ovens, probably the most efficient way of using it known at present, accounted for 5·4 per cent of the total.

From the Report of the Electricity Commissioners for 1922–23, the average number of units generated per ton of coal was 803, which represents 2·8 lb. of coal per unit. Only 11 undertakings generated more than 1 000 units per ton, the figures being 1·8 to 2·24 lb. of coal per unit. Of the units sold, 18·9 per cent was for lighting and domestic use and 67·7 per cent for power, the average price being 5·3d. per unit for lighting and 1·3d. for power.

The number of units used per head of population is interesting:—80 per cent of the population use less than 100 units per annum; 14·7 per cent between 100 and 200 units; 5 per cent between 200 and 300 units; and only 1·1 per cent 300 units and over.

In 1920 the United States used 176 units per head,

against our 60, and in May, 1924, the figure for Chicago was 700, against Manchester's 246.

I should now like to mention, in comparison, the human energy-transformer. The figures are due to Dr. A. T. Schofield. The daily average losses of the human body are $2\frac{1}{2}$ lb. of solids and gases, and 6 lb. of water.

The daily make-up is $1\frac{1}{8}$ lb. solids (dry food), $1\frac{7}{8}$ lb. oxygen, and $5\frac{1}{2}$ lb. water. The $\frac{1}{2}$ lb. difference in water is made up by combustion. This food taken represents 3 400 ft.-tons of energy, or 2·88 kWh or units, of which 3 060 ft.-tons, or nine-tenths, are used in maintaining the heat of the body, and 340 in the active functions of life, in storing energy by physiological processes, or are expended in nervous and mechanical energy.

It will be seen that the useful efficiency is only 10 per cent, and I shall refer to this later.

Fuel oil.—The heat value ranges between 18 500 and 19 500 B.Th.U. per lb. The oil fuel used in Great Britain is under 1 per cent of the weight of coal used, whilst the average price is 80s. 6d. per ton, against the average price of 20s. 5d. for coal.

Gas.—Small producer-gas stations averaging about 500 kW maximum demand show figures comparable with the largest steam generating-stations, the best figures (taken from the report of the Electricity Commission, 1925) being :—

	Lowest aver. fuel consumption per unit generated	Maximum demand	Thermal efficiency
	lb.	kW	per cent
Steam station ..	1·51	48 870	19·85
Producer-gas station	1·54	141	14·76

A careful examination of the figures will also show that the medium-sized station, when equipped with efficient plant, can sell to the consumer cheaper energy than they could if a supply were taken in bulk from a large station some distance away, the losses in transmission being large enough to have a material effect on the efficiency.

Alcohol.—I think that we shall hear a lot more of this fuel in the future. It can be cheaply produced from a number of substances, and when the restrictions now placed on its sale are relaxed it must come into its own.

Its heat value, when 7 to 9 per cent denatured, is about 11 500 B.Th.U. per lb. If free from water the value is 12 420 B.Th.U., and with 20 per cent of water 9 936 B.Th.U.

Let us take the sugar industry now being developed in this country : 1 ton of sugar will yield 40 gallons of molasses, from which 16 gallons of first-quality alcohol can be produced. Other sources available for this country are potatoes, mangolds, and jerusalem artichokes. Cane molasses will produce 69 gallons of 95 per cent spirit per ton.

Incidentally, a company is now working in this country with tanks capable of storing 20 000 tons of molasses, which will produce 1 450 000 gallons of alcohol.

The amount produced in America for power purposes is approximately 58 000 000 gallons annually. The Commonwealth Parliament of Australia has approved of the payment of 4d. a gallon on Australian-produced power alcohol. One company is prepared to spend £50 000 for the erection of plant in Queensland, and the Queensland Government is willing to contribute £25 000.

There is a solid fuel of Continental manufacture called "meta," which has recently been introduced into this country. I have a tablet here. It has been referred to as solid alcohol ; it burns like alcohol and does not evaporate. It is at present being put forward as a portable domestic fuel in place of methylated spirit. The material is metaldehyde, and its composition is carbon, hydrogen and oxygen. The calorific value is 11 450 B.Th.U. per lb.

Water power.—The economical use of energy from water power is generally confined to areas where there is a considerable fall or head of water.

The cost of equipment for handling large volumes of water with low head will generally be so high that it will be found cheaper to buy power from steam generating-stations. This applies to the use of tidal power.

In Canada there are hydro-electric installations in operation generating 3 569 275 h.p., and 600 000 h.p. will be added in 1925.

Wind.—Wind energy can be used economically for very small plants, such as pumping and lighting plants for isolated farms, etc. The force exerted increases as the square of the velocity of the wind. A gentle breeze of 5 miles per hour exerts a force of 0·123 lb. per square foot, a brisk wind of 25 miles per hour 3 lb., whilst a storm of 50 miles per hour gives 12·3 lb.

Solar radiation.—The most economical way of using solar radiation is by means of plant life, the necessary fertilizers being produced as a by-product and returned to the soil.

We could raise the overall efficiency of our uses of energy if we could only cut out some of the transformations that we are now compelled to employ.

Take the case of a steam-driven power station. Our energy emanates from the sun and is conveyed to the earth as electromagnetic waves of the wave-length of heat and light. This is transformed by plant life to chemical energy, and in course of time coal is formed—our usual starting point.

This chemical energy is transformed to thermal energy by combustion ; the thermal energy to mechanical by expansion under heat in the turbine ; and mechanical to electrical by the alternators (which have an efficiency often reaching the high figure of 95 or 96 per cent).

We are now back at the starting point and the energy is again electromagnetic ; no wonder our efficiency is low.

If we now use this energy as light—which is also electromagnetic—we again have a low efficiency, as we have at present no efficient means of confining the wave-lengths to those parts of the spectrum which give us the sensation we call light, but we also get longer waves of heat and in some cases shorter waves of ultra-violet invisible radiation. What we want is cold light.

If we use the energy as heat we obtain the highest efficiency of all ; and if we use it as power we lose

10 to 20 per cent as heat in the motors, although, bearing in mind the magnitude of the losses which we have been considering, this represents a comparatively high efficiency.

A few remarks on the energy of electrical storms may prove interesting. Such storms have a considerable stimulating effect on the growth of plant life.

In a severe thunderstorm the approximate amount of energy stored in the electrostatic field—that is, considering the cloud and the earth as the plates of a huge condenser—is about 700 kWh. The voltage of a flash has been estimated by means of the induction on scale models as 100 million volts, and the current as approximately 78 000 amperes. This represents a tremendous horse-power, but, as it is exerted for an exceedingly short time, the energy is not of a high order, being 13 500 kW-seconds, or 3·76 kWh.

Lightning conductors and aerials when well earthed are to a certain extent a preventive of direct strokes, by lowering the electrostatic stress in their immediate neighbourhood, but people using wireless aerials should in any case take no risks during storms and should earth their aerials outside the house, as even an induced stroke from an object struck some distance away may cause considerable damage to apparatus.

We now come to human energy, or the employment of the 340 ft.-tons per day referred to earlier. This is, by the way, 0·288 kWh, or just over one-quarter of a unit (i.e. worth about 1½d. at the lighting rate in Loughborough).

It will be obvious that we consider this energy to be in a much higher and more valuable class than the energy we buy through a meter. We expend it in nervous and mechanical energy. The more we expend in mechanical, the less we have for nervous or brain energy. This is, of course, apart from the necessary mechanical work (such as the propulsion of a ball) necessary to keep the plant in order. Therefore, the only common-sense way is to buy energy through a meter and use it for every possible purpose. This means more electricity in the home, office and works, or on the farm, in fact everywhere.

More horse-power used per individual means more production all round, as it is recognized that the productivity of a country bears a direct relation to the power consumption per head. This necessarily follows from the fact that the use of more machinery gives greater leisure, and our needs will increase as the means for satisfying those needs increase.

With regard to the use of power in the home, the trouble as I see it is capital cost. If I rent a house which is not electrically wired or equipped and the landlord will not do anything, I should consider it a risky investment to have the house wired and fitted up at my own expense. It is clearly the business of the supply undertaking to make these divergent ends meet and to leave no stone unturned to convince everyone in its area that it will pay them to use power. Then, instead of, as now, only 1·1 per cent of the population using 300 or over units per annum, we might get the population to use 500 units per head and reduce the cost to a much lower figure than it is to-day.

In conclusion, I should like to acknowledge my indebtedness to articles published by Messrs. Rushmore, Peek, and others, for some of the matter included in this address.

DUNDEE SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. S. THOMSON, Associate Member.

(*Address delivered at* DUNDEE, *22nd October*, 1925.)

The duties of those engaged in electrical work are varied and complex. It is therefore natural that men should find themselves gradually specializing in one branch or department, and, in fact, it would be quite impossible for the average individual, at any rate, to be an expert in every department of electrical development. We all wish, however, to be kept in touch at least with what is going on round about us, and there is no better way than by coming together at meetings such as these and by reading carefully the papers and discussions thereon printed in the *Journal*.

Electricity is rendering in a multitude of ways great service to man. This service will go on increasing, and as electrical engineers we should endeavour to develop the spirit of service. I am satisfied that the more of this spirit of service we put into the daily routine, the more will the industry we represent, and we ourselves as members of the electrical profession, prosper, and, what is also important, the more shall we individually get out of life.

We cannot cultivate the idea of service to any great extent without becoming enthusiastic in our work, and all electrical engineers should be enthusiasts. What are we to think of the engineer who does not even take advantage of electricity in his own home; or who uses it for lighting his house but only smiles when cooking by electricity is mentioned; or who shrugs his shoulders when the idea of using a battery vehicle is suggested, or who looks at us with a kind of pitying contempt when the possibility of heating water electrically is hinted at? Such men, however, do, it is to be feared, exist, but they cannot possibly help forward the electrical industry to the extent they should. What is more, they delay the coming of the time when the public will enjoy the full benefits of electricity supply—the very service they should be anxious to help in conferring on their fellow creatures.

Enthusiasm run wild may, however, be dangerous. The man who insists that electricity should be used for every cooking, transport or hot-water-supply problem without thoroughly going into the details of the case may easily do harm. There are questions to be considered, such as the capital cost of the apparatus and the cost of altering existing arrangements, etc.; and these may, for the time being, render a scheme impracticable. To get over these difficulties there is sometimes a temptation to carry the arrangement out in some half-measure fashion which is altogether unsuitable for the economical use of current. The result is failure. After a short trial the scheme is abandoned altogether and harm is done that may take a long time to live down. It is necessary, therefore, to look at every proposition with an open mind. If satisfied that electricity is the right thing in the circumstances, it should be put forward wholeheartedly. If this cannot be done and a case made for electricity strictly on its merits it is better left alone. We have such an excellent commodity that there is no need and no sense in trying to sell it on any other lines than pure merit.

The public cannot, I think, know too much about electricity, and in this connection the British Electrical Development Association is carrying on excellent educational work in bringing to the public notice the uses and advantages of electricity supply. The astonishing thing, however, is that in the past these efforts have been very greatly hampered by lack of funds. The work of the Association is of great value to both the contracting and the supply business, and one would imagine that every engineer, at any rate, must not only be in favour of but admire the educational and propaganda work that is being done. Let us hope, therefore, that the Association will increasingly receive the backing necessary for carrying on the good work.

From a return issued by the Electricity Commissioners, covering the three years 1920 to 1923, I find that the units sold for lighting and domestic purposes and for power amounted to approximately 19 per cent and 68 per cent respectively of the total sales, leaving some 13 per cent of the total for public lighting, traction and miscellaneous uses. These figures show very clearly how the output for lighting has gradually dropped to quite a small percentage of the total.

The figure of 19 per cent includes current sold for domestic purposes other than lighting. The importance of this class of load is now being more fully appreciated, and domestic use for "other than lighting purposes" will year by year demand current in increasing quantities. It will be interesting to watch future development in this direction. How long will it take for the figures of 19 per cent and 68 per cent to be reversed, or will the consumption for power purposes always exceed that for lighting and domestic uses? If the latter, will the ratio remain as at present or will it be reduced? It is probably safe to take it that less than 20 per cent of the houses in the country are wired for electricity, also that the consumption in a house making a fuller use of electricity may be anything up to, say, 30 times that for lighting only. In my own house, lighting accounts for 200 units a year, and other purposes for 4 000 units. I think it is also probably true that a large proportion of the new connections are domestic premises. In the undertaking with which I am connected about 68 per cent of the consumers added each year are "domestic." Although these consumers may, at the moment, individually make only a small demand for electricity, they nevertheless are, in the aggregate,

potential users of current to a large amount. Assume for a moment that the lighting and domestic supplies increased tenfold and that the supplies for power purposes remained stationary. The figures of 19 per cent for lighting and domestic purposes and of 68 per cent for power would then become 70 per cent and 25 per cent respectively of the total.

The demand for power purposes will of course not remain stationary, and certainly no one wishes that it should, but I want to bring out the tremendous possibilities opened up by the domestic load. There seems to be no reason why the sale of current to this class of consumer should not increase much more than tenfold. While therefore there should certainly be no slackening off in the development of the power load, the domestic and lighting loads should be cultivated as energetically as possible.

Whilst the sales for lighting and domestic uses and for power purposes represented respectively 19 per cent and 68 per cent of the total, the revenue was in each case approximately 42 per cent of the total. A tenfold increase in sales for domestic purposes would probably increase the revenue approximately threefold. This is, perhaps, the reason why some engineers seem to fight rather shy of pushing the domestic load, apparently fearing that the whole of their cable system will quickly become fully loaded and that they will soon find themselves in all sorts of difficulties. But why not load up cables? If the business is profitable it should surely be our endeavour to cultivate it to the fullest extent possible. Is the domestic load profitable? Which is the better, a factory making a power demand on the station of 100 kW, or a considerable number of houses making a combined load on the station of the same amount for purposes other than lighting? Such a factory working 44 hours per week might possibly use 4 400 units per week, or say 220 000 units per annum. This would be possible only on a load factor of 100 per cent over the whole of the working hours of the year. Even under these ideal conditions the highest possible annual load factor is only 25 per cent. A much more likely figure would be 20 per cent, giving a consumption of approximately 175 000 units.

Take now 100 houses, each using 200 units for lighting, and assume a tenfold increase in consumption due to current being used for other purposes. The increase in consumption would amount to 180 000 units, or slightly more than the factory consumption. The maximum load on the station for this output of 180 000 units for domestic purposes would, however, due to the better load factor of that class of load, be less than 100 kW and probably not more than 68 kW. Whilst the load factor of the individual domestic installation is low, the diversity factor comes to the rescue to such an extent that the load factor on the station in respect of supplies for domestic purposes other than lighting is considerably higher than that from supplies to factories and other concerns working the ordinary day-hours only. This is easily appreciated when it is remembered that the ordinary day in the home covers about 16 hours for 7 days each week, making a total of 112 hours per week, as against 44 to 50 hours for the factory. Thus, for a given maximum demand on the station, approximately three units will be sold for domestic purposes for every two units taken by factories.

So far then as the cost of generation, transmission to substations, and transformation is concerned, current for domestic supplies can be delivered at the low-pressure terminals of the substation transformers more cheaply than for factory supplies.

This brings us down to the low-pressure distribution mains and service cables. The size of a service cable, to an ordinary house, is generally much larger than would be required for the lighting load only. In certain cases it might be necessary to lay a larger cable, but even then the extra cost is small and, generally speaking, there would be very little, if any, additional outlay on the actual service cables. The same applies largely to meters, and no extra cost would be incurred in the meter-reading and accounts departments, although the consumption of every domestic consumer increased much more than tenfold.

Any possible difficulty in providing current for domestic purposes therefore can only be in connection with the low-pressure distribution mains. These mains, however, must in any case be provided for giving supplies for lighting. The only additional cost, therefore, of supplying current for domestic purposes from the low-pressure distribution mains, compared with supplying current to a factory from a substation in the factory, is that in respect of the outlay in providing additional copper in the distribution mains. The interest and other charges on such additional outlay is certainly more than provided for by the revenue received from the sale of 50 per cent more current than would be taken by the factory for the same loading on the station plant, high-tension transmission cables and transformers.

The problem may be considerably simplified by having transforming substations placed at frequent intervals. This allows a fuller use to be made of the copper in the low-pressure mains without undue voltage-drop. For purely residential districts and thinly populated areas it would seem desirable to adopt a higher pressure, say 3 000 volts, for the distribution mains, using transformers for each house or for groups of houses as required, and in this way ultimately to limit the low-pressure distribution cables fed from each transformer to, say, not more than a few hundred yards in length. It would seem unnecessary to provide any switch- or fuse-gear on the 3 000-volt side of these transformers, and the transformers would simply form part of the cable system. The space taken up by, say, a 100-kW transformer arranged in this way is very small and should easily be provided.

In the foregoing I have been thinking of alternating-current supplies only. It may be weakness on my part, but I find it difficult to do otherwise. In the case of direct-current networks it would appear desirable to consider the question of installing a.c. generating plant in conjunction with rotary converters in the power station and the laying down of new cable extensions beyond a certain distance from the power station on the a.c. system. It is difficult to see how otherwise the ordinary town or city undertaking is to develop the outlaying areas economically. In my opinion the

domestic load is very desirable and profitable and should be cultivated to the fullest extent. I believe that in time it will very largely form the backbone of the electricity supply industry.

I do not know to what extent the wiring and contracting branch of the industry is represented at our Institution meetings generally, but I should like to see a better representation at the Dundee Sub-Centre. Supply engineers are apt sometimes to look upon installation work as a job that any fool can tackle. That is not my view and I think that there is a large scope for good engineers in the contracting business. Certainly examples of shop and house wiring are to be seen that are anything but a credit to the contractor or to the profession. This condition of things is, for the most part, probably due to very keen competition and consequent price-cutting—a feature which we should all wish to see the industry rid of.

Now, unless premises are wired, the supply undertakings cannot sell current, and it is the business of contractors to wire premises. Supply undertakings should therefore welcome every application brought in by contractors and should give contractors, especially the smaller firms just starting business, all the assistance possible. On the other hand, contractors should see to it that only sound jobs are carried out, as otherwise they bring discredit, not only on themselves but on the whole industry, and retard the rate of development.

There is no doubt that, but for the high cost of wiring, new consumers of electricity would be secured at a very rapid rate. To reduce the cost of wiring by using inferior material and rough workmanship will not help matters. Is there no other way of reducing installation costs? I have counted the number of circuits in an ordinary house, not by any means a large one, and find that there are no fewer than 12 circuits—12 pipes and 24 wires—starting from behind the back door to carry current to a few lamps, an occasional radiator or two, and in the kitchen a cooking outfit. According to the tables in the I.E.E. Wiring Regulations these 12 circuits are capable of dealing with 188 amperes, or a load of approximately 41 kW. The lighting circuits alone are sufficient for 6½ kW. The total loading of the lamps installed, at an average of 40 watts per lamp, is under 1¼ kW, and the actual load probably never exceeds ½ kW. The service cable from the street is 7/16 S.W.G., and on the same basis is therefore sufficient for a load of approximately 10 kW. The house referred to is, I take it, quite typical of many others and, if so, it seems to me that there is something very wrong here and that a considerable saving might be brought about simply by reducing the number of circuits. The introduction of the two-part tariff should help in this direction, but it is doubtful to what extent the advantages of this tariff are understood or appreciated by contractors. By unnecessarily keeping up the cost of installation work by putting in a lot of needless material, contractors are, of course, simply standing in their own light. To my mind the ideal system, modified to suit conditions, would be one main circuit controlled by a switch and fuses, each individual piece of apparatus connected to such circuit being fused at the point of connection. In the case of portable apparatus the fuse should be embodied in the plug. Groups of lamps would also be connected through fuses to the main circuit.

This is, after all, the arrangement generally followed in the wiring for motors in works. What should we think if a supply undertaking fixed a large fuse distribution-box at the end of a street and from this ran a twin cable for each consumer in that street? The arrangement would, however, be just about as sensible as the usual method employed in wiring a house. It may be going too far to say that the existing methods of house wiring should be revolutionized, but I am quite sure that it is not beyond the skill of the industry to devise methods for, at the same time, both improving and cheapening installations. I should greatly welcome some good papers on this very important subject.

Any method of providing satisfactory installations at less cost would undoubtedly secure increased business both for contractors and for supply undertakings. There would still remain, however, the difficulty of the tenant occupier; and some system of assisted hire-purchase, or free wiring, seems necessary in order to secure a very large proportion of the present unwired premises. Even now the supply undertaking takes the risk of putting down power stations, transmission cables, substations, distribution mains, service lines and meters. Why not proceed a stage further and wire to the actual lamp or other current-consuming device, thereby securing more consumers per unit length of distribution main?

This would seem a very sound method of reducing the cost of distribution. We all appreciate that systems of assisted wiring are not altogether free from difficulties. A considerable number of such schemes are, however, in operation, and for the most part with apparently satisfactory results. I think that this is a matter to which all supply engineers will sooner or later have to give their serious attention.

I do not wish to discuss the different designs of cooking apparatus. I have already said enough to show the importance which I attach to electric cooking. Apparatus has now reached such a stage of development that no one need be afraid to recommend his best friend to buy it, if the latter can afford the outlay and is unable to obtain the articles he requires on hire.

There is really nothing wrong with the apparatus or with the cost of using it. The initial cost is, however, a difficulty, and not every one is in a position to purchase a cooker, however great may be the desire to enjoy food cooked in the best way. Sooner or later I am satisfied that all supply undertakings will appreciate the necessity of giving their consumers facilities, on easy terms, for cooking by electricity.

The use of electricity for heating has increased very rapidly during recent years, and electric fires are now available in almost endless variety. As one unit of electricity contains a fixed number of heat units, all such fires have, in one sense, an equal efficiency, viz. 100 per cent. What may, however, be called the effective efficiency varies very considerably, and it is always necessary when advising on the use of electric heating to try to ascertain exactly what is the duty required of the heater; otherwise the best results cannot be expected. In this connection it is well to remember

that the best condition for working is to have warm feet and a cool head. For example, a small amount of heat applied under a desk or table from, say, a 250-watt fire will frequently give, at one-eighth of the cost, better results than a 2 000-watt fire placed in the wrong corner of a room.

The heating of water offers some very interesting problems, and while it may be difficult to see how electricity can compete on cost with coal or coke for heating large quantities of water, there are many cases where the matter is not nearly so hopeless as may at first sight appear. The very high efficiency of the apparatus, the ease with which the water may be heated at the points of use, and the absence of all labour, fumes, dust, etc., are frequently sufficient to turn the scale entirely in favour of electricity. Water-heating also opens up possibilities of securing a considerable and steady 24-hour load.

In premises making a sufficient use of electricity for general purposes, to cover all standing charges it would seem that an additional unmetered supply taken continuously over the 24 hours could be given at a low, but at the same time remunerative, fixed charge. A properly lagged tank fitted with a 250-watt heater should provide over 18 gallons of water per day at a temperature of about 140° F. A charge for this service of 7s. 6d. per month would give the supply undertaking a revenue of £18 per kilowatt of demand. Are there many undertakings likely to refuse such an additional revenue from existing consumers? Would many not gladly accept less?

The battery vehicle does not seem to make in this country the progress one would have expected. We all know the dislike many engineers have for storage batteries, a dislike brought about in many cases, I believe, due to the installing of a battery for a certain purpose and using it for duties for which it was never intended. We should, however, be just, and in such cases it is hardly fair to blame the battery. Several large firms in London and elsewhere are using battery vehicles in increasing numbers, and I take it that they are doing so because they find it pays. For city and town work the advantages of the battery vehicle are really well known, if not always readily admitted. Are we engineers encouraging the use of such vehicles to the extent we might? At Townhill power station we have a 3½-ton battery vehicle and a battery locomotive, and I can safely say that very few parts of the station equipment perform their duties as regularly and with as little fuss as do these two battery vehicles. There are two other vehicles on our system each using about 14 000 units a year, and from the revenue point of view such vehicles are therefore worthy of consideration. The surface of our roadways generally is being steadily improved, and I really think that we should give the use of battery vehicles in transport problems more attention than we have perhaps done in the past. I hope that we shall soon become more familiar with the appearance of such vehicles on our streets.

I am glad to notice that the supply of electricity to farms is receiving increasing attention. The farmer requires a supply in his home for lighting, cooking and heating, just as much as other people do. He also requires light in all the farmstead buildings, in addition to a supply of power for an almost endless variety of purposes in connection with the working of his farm. Where 6 600-volt or 11 000-volt lines or cables exist there is no difficulty in giving a supply from such. In my own area a supply is at present given to some 50 farms and I know how greatly the advantages are appreciated by the farmers. I look forward to a steady increase both in the number of farms connected and also in the number of units used per acre. There is no doubt about the advantages arising from a supply of power being always available at a farm, and it is, I think, for us to see that electricity is brought within reach of as many farms as possible. In the interests of the country we cannot do this too soon.

We still hear a good deal about "cheap and abundant supplies of electricity"—a rather unfortunate phrase, I think, and one that is apt to do more harm than good. The price of electricity in this country is not unduly high, and is certainly not responsible for trade depression. It is questionable whether many industries which are now finding it difficult to make ends meet would be appreciably better if supplied with free electricity.

The price of electricity for various uses should very largely be regulated by the cost of the alternative methods of obtaining the power, light or heat required. In practically every case electricity offers advantages which are not available by the other methods, and such advantages are always worth something.

The way to cheapen electricity is to develop and push its use for all purposes and carefully to grade the price to suit the different purposes for which it is used.

We require foresight and, above all, an implicit belief in the commodity we have to sell. If only everyone connected with the manufacture of electrical plant and the generation of electricity, and especially those engaged in the sale of current, completely possessed these qualities, the country would be satisfied with the price of electricity and the sufficiency of the supply.

A GENERAL SURVEY OF THE HIGH-TENSION SWITCHGEAR FIELD.

By S. FERGUSON, Member.

(*Paper* received 19th January, 1925; read before the* EAST MIDLAND SUB-CENTRE *10th February*, 1925.)

SUMMARY.

The object of the paper is to aid the operating engineer in laying out high-tension switchgear schemes. It deals with the evolution of switchgear, giving the contributing factors in its development. The present-day types are scheduled and the principal features compared in the light of the requirements of good switchgear. The most suitable type to meet modern conditions is indicated as being a form of metal-clad, compound- or oil-filled, interlocked, draw-out unit for pressures up to 66 kV. A plea is made for the standardization of this type as the best course to adopt for effecting a reduction in switchgear prices.

Various schemes of connections for central stations and substations are considered, and the advantages and disadvantages of different arrangements recorded. A number of typical installations are shown for super-power stations, and particularly super-tension layouts for indoor and outdoor service. The working principles of oil circuit breakers are considered, together with the various factors which affect breaking capacity.

Section 1.

PRESENT-DAY TYPES AND THEIR EVOLUTION.

SCHEDULE OF TYPES.

The following is a brief schedule of present-day types of high-tension switchgear :—

(1) Open floor mounting.
(2) Panel mounting.
(3) Cellular (brick or concrete).
  (*a*) Non-interlocked.
  (*b*) Interlocked.
(4) Metal-enclosed, stationary, air-insulated.
  (*a*) Non-interlocked.
  (*b*) Interlocked.
(5) Metal-enclosed, truck, air-insulated, interlocked.
(6) Metal-clad, draw-out, compound-insulated.
  (*a*) Truck type, completely interlocked, horizontal isolation.
  (*b*) Carriage type, completely interlocked, horizontal isolation.
  (*c*) Slung type, completely interlocked, vertical isolation.
(7) Metal-clad, draw-out, oil-insulated, interlocked.
(8) Outdoor type.
  (*a*) Open floor mounting.
  (*b*) Cubicle floor mounting.
  (*c*) Pole mounting.

* The original paper consisted of eight Sections, of which five are here published. The Sections omitted were entitled "Introduction," "Protective Gear," and "Circuit Equipments" respectively.

EVOLUTION OF HIGH-TENSION SWITCHGEAR.

It would appear to a casual observer that the numerous present-day types of high-tension switchgear have been dictated by fashion. Such is not the case, however, as there are many reasons for the continual changes which have taken place during the past 20 years. Environment has had a profound effect on the evolution of switchgear. In England, with its dense, industrial areas, switchgear has taken a condensed form and a relatively small amount of outdoor gear is in service. In America, with its large stretches of open space, outdoor switchgear has been developed to a much greater extent in order to avoid high building costs as transmission voltages have increased.

Concentration of power due to the rapid growth of power schemes has made it all the more imperative that switchgear should not be a source of weakness to the system which it is intended to protect. The open cellular principle was introduced by Dr. Ferranti in 1894, the ideas underlying the design being the entire elimination of earthed metal work in the vicinity of high-tension conductors, and the provision of a cellular housing with a view to the localization of damage. This type of switchgear proved dangerous to the attendant, was non-fireproof, and was only suitable for the control of small amounts of power.

In order to protect the operator the panel-mounting type was evolved. All high-tension gear was mounted behind flat-back control panels which protected the attendant during switching operations but did not protect him sufficiently when cleaning or repairing the oil circuit breaker. A more satisfactory arrangement was the use of concrete or brick cells, closed in with steel doors, for the switchgear housing. As a result of the rapid increase in plant capacities, cellular gear had to be correspondingly increased in size until several floors of the central station were needed for its accommodation, with a consequent increase in building costs. This type of construction was also used initially for substations, but it was too costly, lacked portability, and took too long to erect. Consequently, the steel cubicle type was adopted because it was factory-built, portable, and could be erected with ease and rapidity.

Experience showed that with the ever-increasing size of apparatus the cubicle construction was not altogether the best as regards accessibility of gear. This was specially so where it was desired to erect cubicles against a wall and to obtain access from the front only. In consequence a demand developed for the truck type of cubicle in which all the parts required to be accessible could easily be withdrawn from the live portion of the equipment. The draw-out idea, as

applied to built-up sheet-steel cubicles, was introduced in this country as early as 1903. The demand for this class of gear was also prompted by the desire for increased safety to the operator. It was not an uncommon occurrence for one of the connecting rods on a set of mechanically-operated isolators to break, thus giving the operator a false sense of security. Compared with the totally-interlocked steel cubicle, the truck had a great advantage in its increased safety of operation and accessibility, but it did not come into its own for a considerable time, due to the fear that the plug-and-socket portion might not give satisfactory service. Subsequent experience proved the gear to be sound, and the demand became considerable.

The development of larger power stations along with underground cable systems brought in its train many factors which reacted on switchgear design. The interruption of heavy short-circuit power produced excessive surges, and under these conditions the air clearances, which had hitherto been considered adequate, were broken down. The solution of this problem was either to increase the air clearances and thus make the switchgear more bulky, or to replace the air by a more stable dielectric such as compound or oil. In order to meet these conditions the metal-clad compound-filled draw-out type was developed contemporary with the truck cubicle. The commercial design of this apparatus was first undertaken by a British maker in 1905, when it was installed by the electrical companies operating on the North-East Coast.

Reviewing the evolution of switchgear, the following factors have contributed largely to the result :—

(1) Space considerations. These were brought into prominence by high building costs for central stations and substations in built-up areas. The difficulty in getting consumers to allow sufficient space for substations and the desire to increase the capacity of generating units in existing stations have led to condensed forms of switchgear.
(2) Stability. The dependence of large industries on the public supplies has increased the demand for reliability and continuity. This factor has contributed to the introduction of dielectrics having a greater stability than air.
(3) Protection to life. This has been increased by the Home Office Regulations and "safety first" propaganda, resulting in the encouragement of draw-out switchgear.
(4) Low cost. The demand for cheap electric supplies, which has been the main factor in the development of factory-built control units.

Deciding Factors in the Selection of a Suitable Type.

In making a fair comparison of different types the following factors have to be considered, and the relative importance to be attached to each will vary according to the conditions to be met. Each factor can only be applied relatively to the various types from which a choice is to be made.

Schedule of factors.

(1) Immunity from breakdown due to the following causes :—
   (a) Surges.
   (b) Instability of the dielectric.
   (c) Vermin.
   (d) Dust, dirt and moisture.
   (e) Electromagnetic forces on short-circuit.
   (f) Thermal effects on short-circuit.
   (g) Explosions.
(2) Protection to life of operator.
(3) Localization of damage and reduction of fire risk.
(4) Ease of control for normal switching operations.
(5) Facilities for inspection and repairs to circuit breaker.
(6) Space occupied.
(7) Time taken to install.
(8) Portability.
(9) Cost.
   (a) Capital.
   (b) Depreciation.
   (c) Maintenance and cleaning.
(10) Facilities for carrying out extensions and modifications.
(11) Facilities for installation of a spare circuit breaker.

Comparison of Features.

The numerous present-day types of high-tension switchgear are well known and therefore no attempt has been made to describe them. Metal-clad oil-insulated draw-out switchgear is an exception. This type is an entirely new development and has only recently been put into commercial use. An illustration is given in Fig. 6. Oil insulation is used in place of compound insulation, but with slight variations the same unit can be used for either.

Each type derives its individuality by virtue of a particular combination of the seven fundamental features given in Table 1, and these will be discussed separately.

Insulation.

The connections between individual pieces of apparatus may be insulated by air, compound or oil, and it is the relative merits of these dielectrics which will be considered. In the following remarks, air-insulated gear will be referred to as "open gear," and compound- or oil-insulated gear as "filled gear."

Space occupied.—The space occupied by switchgear is almost entirely dependent on the clearances between phases and to earth through the surrounding insulation.

Fig. 1 shows three curves, A, B and C, giving the breakdown voltages for various thicknesses of air, compound and oil respectively. It is clearly demonstrated that the dielectric strength of air is very much inferior to that of compound or oil. In consequence, the space required for the accommodation of filled gear is very much less than that needed for open gear. This advantage is reflected in the reduced building costs of the switch house.

The relative space occupied by cellular and filled

gear of comparable breaking capacity is illustrated by Figs. 2 and 3, which are drawn to the same scale.

As an example of the large dimensions which metal-enclosed air-insulated gear assumes at the higher voltages, Fig. 4 is an illustration of a 33-kV substation cubicle with bushing-type transformers. Further space would be required for the accommodation of metering transformers.

Surges and instability of dielectric.—A comparison of air, compound and oil dielectrics brings out the difference in behaviour of a gas, liquid and semi-solid under the action of an electrostatic field. Air, in common

TABLE 1.

Feature	Methods adopted
Insulation	Air Compound Oil
Isolation	Stationary Draw-out
Enclosure	Open Metal Masonry
Interlocks	None Complete
Location	Indoor Outdoor
Control	Direct Remote mechanical Remote electrical
Busbar selection	Isolating switches Change-over of plugs Oil isolators Double circuit breakers

with all other gases, is a very unstable insulator and its dielectric strength is affected, to a certain extent, by temperature, pressure and humidity. The most serious disability of air as an insulator lies in the fact that its dielectric strength is reduced considerably by ionization, which is generally caused by local breakdown at points of excessive potential gradient or by the leakage of ionized gas and semi-conducting oil vapours from breakers.

The ejection of gas synchronizes with the voltage surge caused by the interruption of short-circuit power. In the case of totally-enclosed air-insulated gear the ionized gases accumulate owing to bad ventilation and, in consequence, flash-over may take place as a result of a voltage surge on the system. The effect is cumulative, because a number of sparks may quickly follow at a much lower voltage due to the increased ionization produced by the preceding flash-over. Nearly 50 per cent of failures are due to breakdown in air after the fault has been successfully cleared. Flash-overs of 6-in. have even occurred across the open blades of isolating switches on 6 500-volt systems.

In the case of filled gear the dielectric is stable, has a greater spark-lag than that of air and has a sufficiently high dielectric strength to withstand voltage surges on the system. The rupture of insulation requires not only a sufficiently high voltage but also a definite minimum amount of energy. This accounts for the time-lag between the application of voltage and the breakdown of the material. The rupturing energy required for oil and compound is much greater than that for

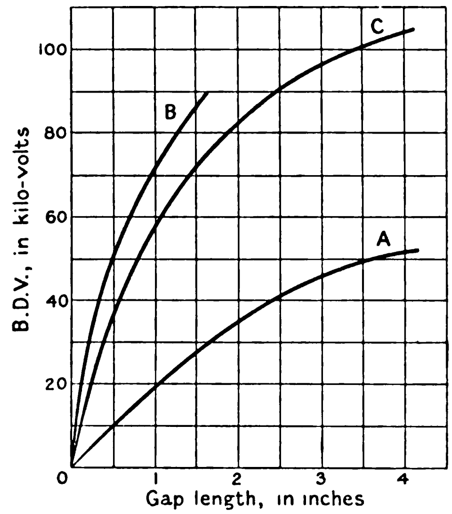


FIG. 1.—(Breakdown voltage)/(thickness) curves for air, compound and oil insulation.

air. If similar oil-, compound- and air-gaps are set for breakdown at the same low-frequency voltage, a much higher transient voltage will be required to rupture the oil and compound gaps than that necessary for the air-gaps, thus demonstrating the greater spark-lag of oil and compound.

Fig. 5 illustrates the difference in spark-lag for air and oil sphere-gaps set for breakdown at the same continuously-applied low-frequency voltage. Curve " A " is for air, and curve " B " for oil.*

Compound, in common with other solid dielectrics, has a greater spark-lag than oil.

Oil is self-healing after a breakdown, and with commercial oil the voltage required for a second breakdown is increased due to drying of the oil.

Vermin.—Vermin, always a menace to electric supply, can often bridge the clearances employed in air and so cause short-circuits. Even if the connections are completely taped, as is common practice in important breaker cells, there are always exposed parts, such as

* The curves have been prepared from data presented by Hayden and Steinmetz in a paper entitled "Disruptive Strength with Transient Voltages," *Transactions of the American Institute of Electrical Engineers*, 1910, vol. 29, p. 1125.

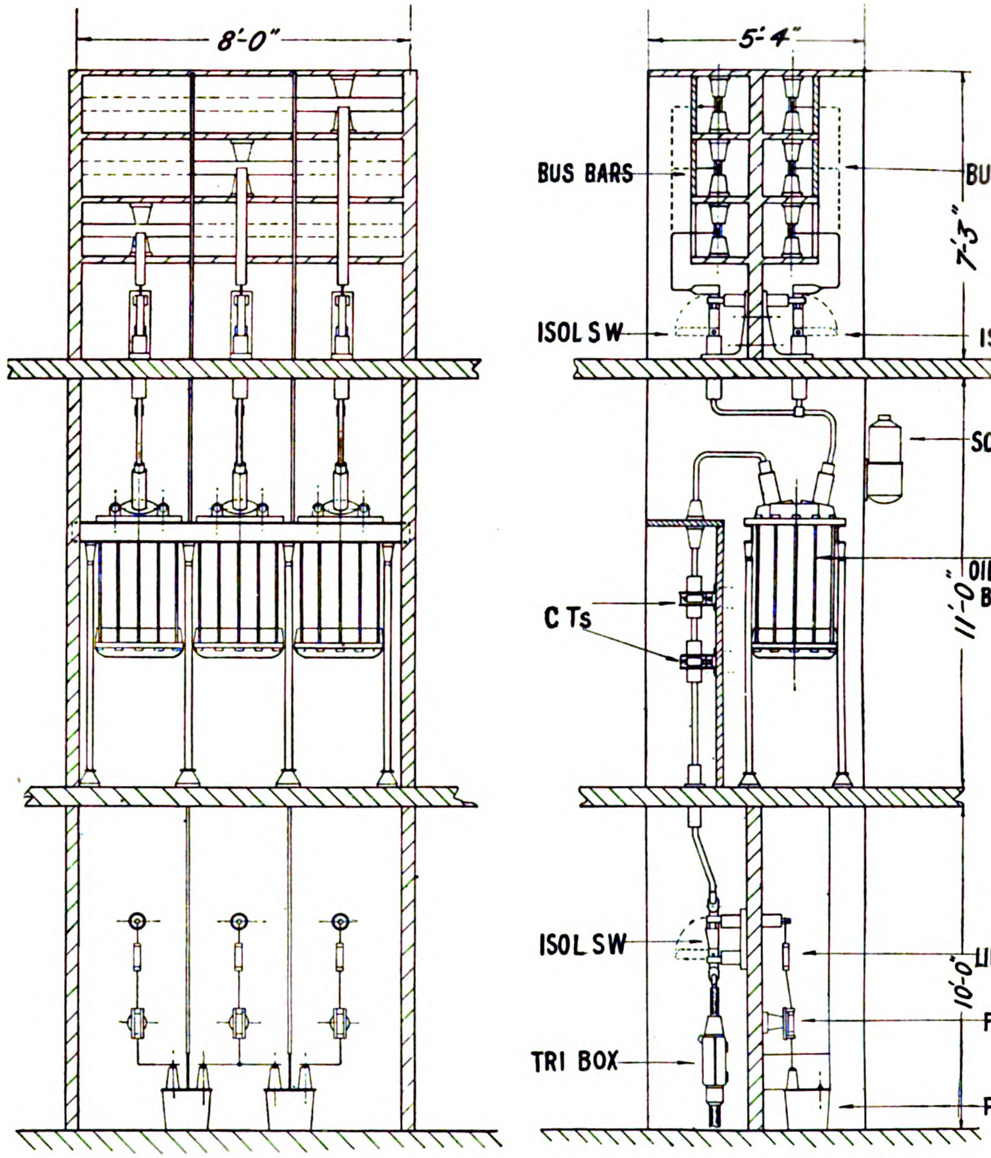


FIG. 2.—Typical cellular switchgear.

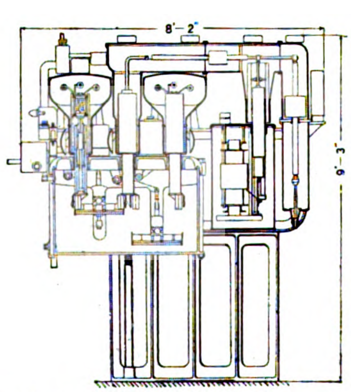


FIG. 3.—Metal-clad switchgear unit of comparable breaking capacity to the cellular gear shown in Fig. 2.

isolating switches, which have been known to be bridged by rats. In large central stations employing air insulation, switchgear occupies several floors, with many exposed points of possible breakdown. Such is not the case with filled gear and consequently there is no risk of shut-down due to this cause.

Dust, dirt and moisture.—Dust, dirt and moisture can collect on open gear, necessitating periodical interruptions of supply for cleaning and maintenance. Filled gear is dirt- and dust-proof on account of the close "metal cladding" of the external insulation. The dielectric strength of oil is reduced considerably by the absorption of a small percentage of moisture, but this is so high and the factor of safety is such that in practice no serious difficulties are introduced on this score.

Electromagnetic forces on short-circuit.—The value of

the electromagnetic forces varies inversely with the distance between conductors, so that with the smaller spacings employed on filled gear the forces are greater than those on open gear. The possible maximum

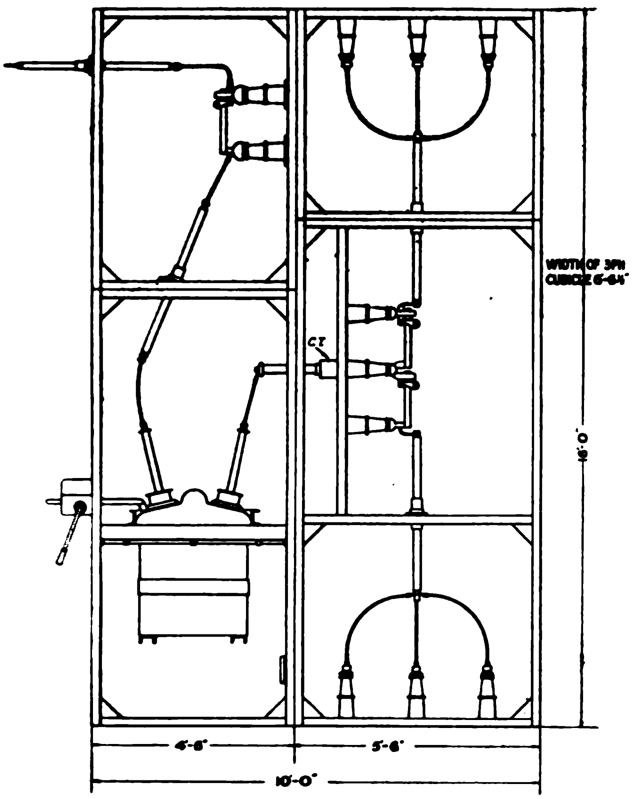


FIG. 4.—33-kV air-insulated substation cubicle.

forces can, however, be calculated to a reasonable degree of accuracy and the conductors supported accordingly. In the case of compound-filled gear the conductors are supported throughout their entire length.

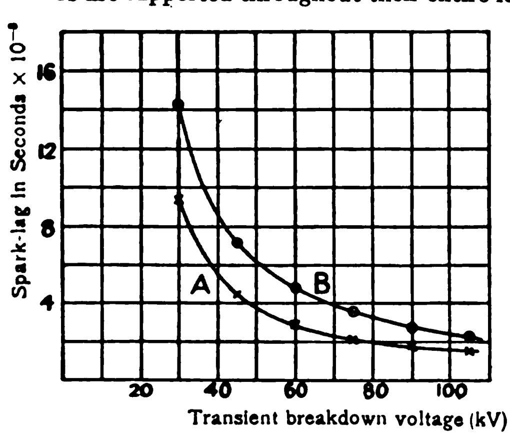


FIG. 5.—(Transient breakdown voltage)/(time) curves.

Explosions.—With open gear there is always the danger of an accumulation of explosive gases in the air, which may be exploded, with consequent danger to the equipment. A case is on record where a sub-station building was demolished through this cause, 8 tons of concrete, etc., being hurled a distance of 20 ft. The spaces where such gases can accumulate in filled gear are eliminated. The danger in the breaker is common to all types, and the tanks, top plates, etc., are usually designed to withstand any possible explosive forces developed in the breaker structure.

Protection to life of operator.—In the case of filled gear, accidental contact with live metal is impossible on account of the complete earthing shield. Even when the breaker is removed for inspection there still remains a completely earthed envelope over all the live contacts. Filled gear does not require any cleaning for the purpose of maintaining high insulation. It is in

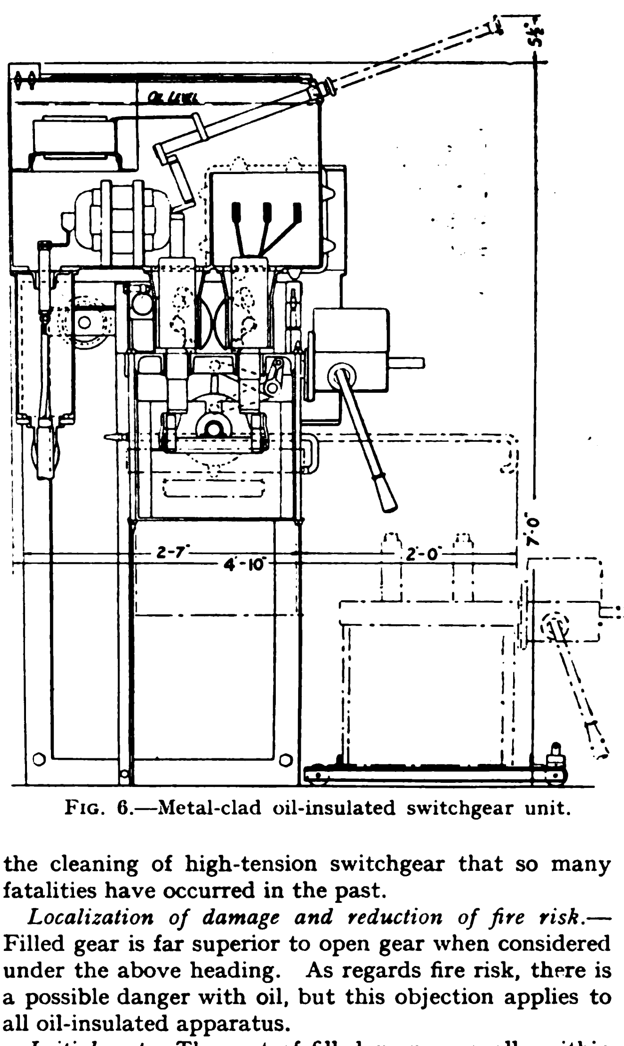


FIG. 6.—Metal-clad oil-insulated switchgear unit.

the cleaning of high-tension switchgear that so many fatalities have occurred in the past.

Localization of damage and reduction of fire risk.—Filled gear is far superior to open gear when considered under the above heading. As regards fire risk, there is a possible danger with oil, but this objection applies to all oil-insulated apparatus.

Initial cost.—The cost of filled gear is usually within 10 per cent of that of open gear. In special cases where the latter is spread over several floors and complete interlocks are required, the former has the lower initial cost.

Depreciation.—There is more deterioration of contacts and current-carrying parts with air than with oil or compound insulation.

Facilities for modification.—One of the main objections urged against compound-filled gear is the lack of

accessibility of the current-carrying parts for modifications. This applies to instrument transformers, particularly when it is desired to alter ratios. In order to overcome this objection some of the later designs embody oil-insulated transformers, whilst the busbars, etc., are embedded in compound, thus making a compromise.

Facilities for carrying out extensions without interrupting the supply.—Compound-filled gear is not so convenient for carrying out extensions as air- or oil-insulated gear, but where duplicate busbars are provided it is always possible to work on one set whilst normal running is maintained on the other set. With oil filling it is more convenient to carry out extensions to the busbars than is the case with compound. Furthermore, there is no possibility of air pockets being formed. In the case of compound, this is a possible danger, due to the difficulty of preheating the busbar connecting chambers when filling on site. A metal-clad oil-insulated switchgear unit is shown in Fig. 6.

Cooling conditions.—The different cooling capacities of oil, air and compound affect the maximum current densities permissible with the three types of insulation. In the order stated, the approximate ratio of densities is 1·4, 1·0 and 0·6.

ISOLATION.

Whatever type of gear be employed, it is necessary to provide means for isolation in order to carry out inspection, cleaning and repairs to the breakers. From an analysis of the Factory Inspector's Report, covering a period of four years, 1911–1914, before truck gear became so popular, it was found that the average number of accidents occurring on switchboards, due either to faulty design, or to cleaning, repairing and handling apparatus supposed to be dead, represented 72 per cent of the total.

The two methods of isolation are :—

(1) Stationary method by means of isolating switches, the breaker when isolated remaining in its normal position.

(2) Draw-out method, the breaker being withdrawn from the live parts.

(1) *Stationary method.*—Air- or oil-insulated switches may be employed, and it is necessary to provide these on both sides of the breaker. Cellular switchgear employing this method is shown in Fig. 2. A unit employing oil-immersed isolating switches is illustrated in Fig. 26.

(2) *Draw-out method.*—The breaker is withdrawn bodily from the live parts, this being made possible by the provision of plugs and sockets. Two variations in the draw-out method are in use, i.e. the breaker may be withdrawn either horizontally or vertically. In the case of the latter, large breakers are withdrawn by a lowering motor. The vertical method requires less floor space, and inspection can be carried out without encroaching on the passage way. A further advantage of this method is that it provides a more direct run of connections between the breaker and busbars.

A unit having vertical isolation is shown in Fig. 3, and one of the horizontal type in Fig. 7.

Draw-out gear is very popular at the present time and is gaining favour not only in this country but in America, where it was introduced only a few years ago. The initial objection raised was the necessity for plug-and-socket connections, but entirely satisfactory results have been obtained by the incorporation of self-aligning features. The main advantage lies in the fact that, when the breaker is withdrawn, one can see definitely that the gear about to be handled is dead. There is never the same certainty with the stationary method.

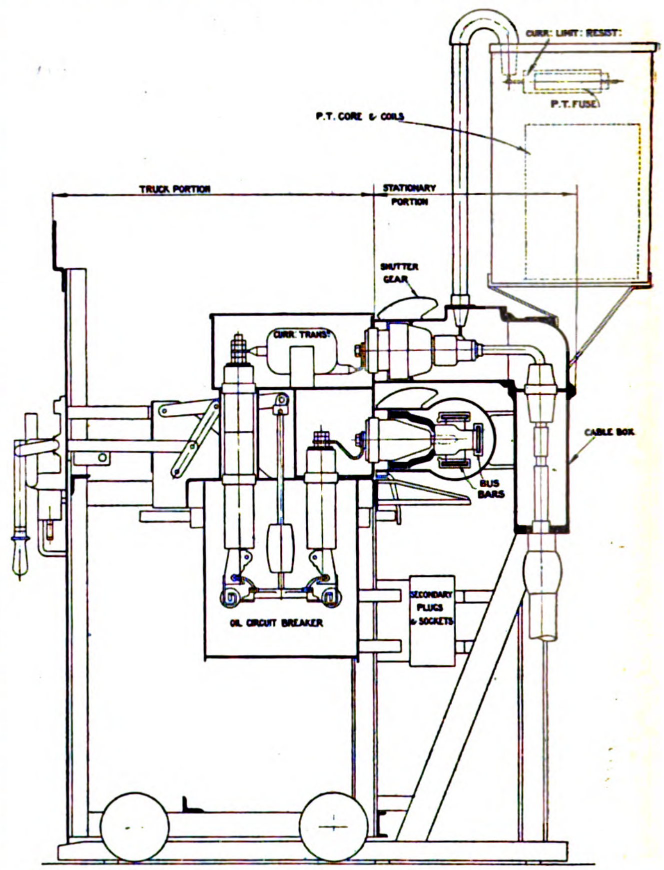


FIG. 7.—Metal-clad compound-filled horizontal draw-out truck-type switchgear unit.

The draw-out feature gives more facilities and greater accessibility for inspection and repairs to the breaker. A spare can be run into position in a much shorter time than is necessary in the case of stationary gear. This enables a change in the circuit equipment to be carried out whilst the spare breaker maintains the supply.

It is comparatively simple to provide complete interlocks on draw-out gear, and these are invariably embodied. On the withdrawal of the breaker the live portions are automatically shielded by safety shutters so that persons cannot make accidental contact. With stationary gear, reliance has to be placed on the human element and there always remains the possibility of doors being left open.

The draw-out feature adds 7 to 10 per cent to the cost, but is usually no more expensive than the completely-interlocked stationary type, over which it has many advantages.

On rare occasions very light trucks have been blown out of their housing due to explosion in the cubicles. This has doubtless occurred after the breaker has operated, as the truck is locked in when the breaker is closed. The author is not aware, however, of any case where this has happened to a heavy truck. It is comparatively easy to safeguard against this trouble by the provision of a positive locking-in arrangement. Fig. 8 shows a heavy-duty truck cubicle in which the horizontal

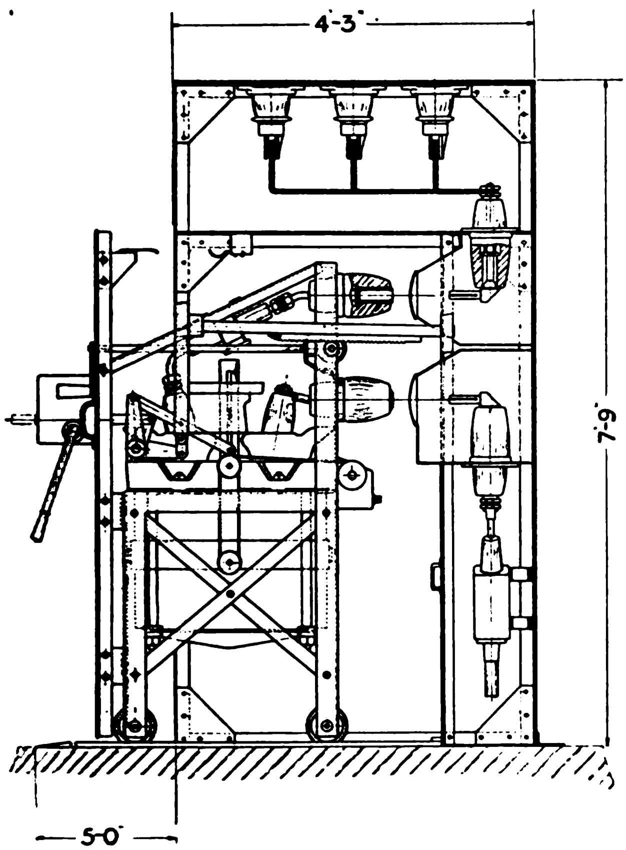


FIG. 8.—Heavy-duty air-insulated draw-out truck cubicle.

method of isolation is used. The truck is withdrawn by means of a manually-operated rack and pinion.

ENCLOSURE.

In this respect, switchgear may be classified under three headings :—

(1) Non-enclosed	Indoor, Outdoor
(2) Metal-enclosed	Cubicle, Metal-clad
(3) Masonry-enclosed.	Cellular

In comparing the above variations of enclosure, the first affords no protection to life, the second affords definite protection in that the metal enclosure can be readily earthed, whilst the third, being in the nature of a semi-insulator, is not quite so safe to handle as the metal-enclosed. If a flash-over to earth occurs on metal-enclosed gear, it will be a dead earth and will be maintained until the fault is cleared by the protective gear, whereas with masonry the arc will in all probability be extinguished after the pressure-rise has subsided, unless the arc strikes to earthed metal. In the former case there would be no danger in touching the enclosure, but in the latter there is a risk to the attendant. The majority of engineers would prefer a fault to show up definitely and be rectified.

The open type of gear is prohibited in this country by the Home Office Regulations, unless the live conductors are above 8 ft. from the ground or made absolutely dead from without before handling. This 8 ft. must be measured from the bottom sheds of the porcelain insulators, in view of the fact that such sheds will have a potential above earth. In America the open construction is used extensively for 22 kV and upwards, whilst on the Continent masonry enclosures without phase separators are employed.

The reasons put forward by American engineers for their preference for open gear are as follows :—

(a) Masonry structures must be considered to be conductors for voltages in excess of 11 kV, and consequently this construction takes up more space than open gear.
(b) Masonry structure entails more expensive building and construction.
(c) Inspection and repairs are easier with open gear, and incipient trouble is more readily detected.
(d) At higher voltages the destructive effect of an arc is less, owing to the small currents dealt with, and fireproof structures are not so essential.
(e) There is less danger of mistakes on the part of an attendant when operating open-type gear, as he can see the whole of the connections and the position of isolating switches.

Whilst there is much force in the above contentions, separate compartments for oil breakers are practically essential in this country to meet the Home Office Regulations, as shown in Fig. 36.

Space occupied.—Some engineers are prepared to allow clearances to masonry 20 per cent less than those required to earthed metal, but generally the safer course is adopted and full clearances are allowed, on the assumption that masonry is a conductor. This increases the size of masonry-enclosed gear when compared with equivalent metal-enclosed gear. With the larger sizes of the former it is frequently necessary to occupy two or three floors, with consequent possibilities of operating mistakes. A masonry structure is illustrated in Fig. 2.

Localization of damage and reduction of fire risk.—Masonry structures are more fireproof than sheet-steel cubicles, and arcing which is not cleared promptly will burn holes through the latter and spread to adjacent cubicles.

Factory-built units.—One of the chief points of advantage of metal-enclosed gear is that it can be built up as self-contained units in the factory. Factory-built units are illustrated in Figs. 3, 4, 6 and 7.

It is generally conceded that erection work on site costs about three times the amount for identical work done in the factory, and it is not carried out under the same degree of supervision. Metal-enclosed gear has a strong claim not only as regards cost but also on the score of soundness of construction. Self-contained units are portable, quickly installed, and easily removed foı modifications. This is a distinct advantage where the system outgrows the breaking capacity of the breakers in a particular location, in so much that they can be readily removed to a less important part of the system.

Interlocks.

It is desirable that the human element should be eliminated as far as possible in the manipulation of switchgear, especially in view of the large proportion of accidents which occur thereon and the necessity for prompt action with full self-control in cases of emergency. Interlocks are now generally called for, but some engineers object to them on the grounds that they do not allow temporary connections to be made. This is really an advantage, in that it avoids risks that would be taken if such work were attempted.

Complete interlocks are very cumbersome on masonry-enclosed gear occupying several floors, but it is under these conditions that they are most needed. The cost is also very great because interlocks have to be specially designed for each job.

All modern types of draw-out gear can be easily fitted with complete interlocks and are generally so supplied.

A complete system of interlocks should fulfil the following conditions :—

(*a*) It should not be possible to break or make the circuit on the isolating device until the breaker is in the "open" position, but it must be possible to check the operation of the latter when in the completely isolated position.

(*b*) No part of the gear should be capable of being exposed when alive.

(*c*) Where the isolated apparatus is earthed before being handled, it must be impossible to reclose the isolating device until this earth has been removed.

The most prevalent operating mistake is the opening of isolating devices while current is passing, and many people protect against this contingency only by the provision of an interlock between the breaker and the isolating device so that the latter cannot be opened until the former is in the "open" position. This interlock is usually simple and cheap, but it is questionable whether half-measures are satisfactory. In reckoning the cost of complete interlocks it should be borne in mind that the cost of attendance, maintenance and cleaning is reduced because a less skilled grade of labour can be employed.

Location.

Outdoor gear has had a very limited application in this country and on the Continent, but it is used extensively in America. There is no doubt whatever that for super-tension gear this form of construction is coming into favour, due to an overall saving of from 15 to 20 per cent for voltages of 44 kV and upwards. No buildings are required except for the control panels. A 135-kV outdoor oil circuit breaker is shown in Fig. 44. The cost of outdoor switchgear itself is 10 to 15 per cent more than that of corresponding indoor gear, the overall saving being due to the difference in cost between the structural steelwork and the buildings. The space occupied by super-tension gear is very considerable, and the building costs represent an appreciable portion of the total costs.

Many engineers question the wisdom of installing outdoor gear, in view of the difficulties experienced when carrying out routine testing and cleaning. Furthermore, when urgent erection or repair work has to be undertaken regardless of weather conditions, outdoor gear is at a serious disadvantage. It is a very difficult job to exclude rain from the oil tanks when a breaker is opened up during a storm. The difficulty is overcome in the cubicle type of gear illustrated in Fig. 9. It consists of indoor apparatus mounted in weatherproof cubicles. This arrangement affords some protection against driving rain when the oil tank is lowered. The cubicle type of gear is being employed in America on a number of schemes for voltages up to 22 kV.

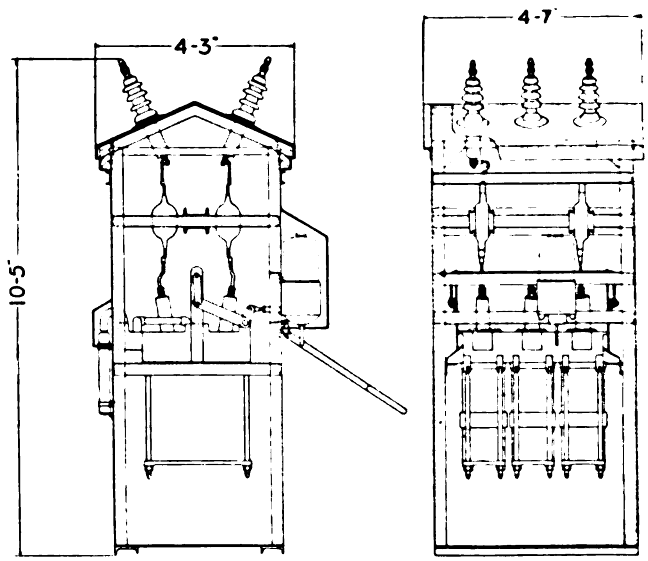


Fig. 9.—Cubicle floor-mounting type of outdoor switchgear.

Outdoor gear obviously takes less time to erect, as it is merely necessary to provide foundations for the supporting structure.

Control.

Direct control is only employed in central stations for plants of very small capacity, say up to 5 000 kVA. It is not desirable to exceed this limit, for the following reasons :—

(*a*) The attendant must have full self-control if he is to act promptly in cases of emergency. This is best attained by removing the high-tension gear from the point of control.

(*b*) With larger sizes of plant there is more likelihood of explosions and other dangers, and hence remote control increases the safety of the operator.

(*c*) With remote control the switchgear can be located in a fireproof building in any convenient position, and at the same time the control panels can be so situated that the operator has sight of the generating plant.

(*d*) The instruments may require attention while the plant is running, and this is much more conveniently done when they are mounted on a separate control board.

Remote control.—Two methods are in common use :—

(1) Mechanical.
(2) Electrical.

(1) *Remote mechanical control.*—Where the breakers are not too large and the control board can be located in close proximity, mechanical control may be quite suitable. On the other hand, where heavy breakers have to be operated, or the distance is considerable, it is advisable to adopt remote electrical control. If the automatic trip coils are not fitted on the breaker itself, the inertia of the bell crank levers and connecting rods will reduce the opening speed of the breaker. Backlash in the mechanical driving system will reduce the final pressure on the contacts of the breaker when in the closed position. This is a serious matter in the case of laminated-brush contacts, as their current-carrying capacity depends on the contact pressure employed.

(2) *Remote electrical control.*—The methods commonly employed are either solenoid or motor operation. The former is cheaper and generally preferable if a d.c. supply is available. If not, it is necessary to adopt motor operation or install a battery and motor-generator.

Electrical operation enables the control gear to be condensed to a minimum so that centralization of control is carried out to its highest degree. It is common practice to energize each solenoid from its own contactor, which is operated from the control board. This removes heavy control wiring from the latter and also the interruption of inductive circuits at the point of control. With electrical control the breaker is free to trip without any external mechanical load, as is the case with the other method.

On one or two recent American installations a combination of electrical and mechanical operation has been employed. The three phases are segregated into separate fireproof compartments and, although remote electrical group operation is employed, the three poles of the breakers, isolators, etc., are coupled mechanically over long distances. The solenoid is mounted above the middle pole of the three so that only the two outer poles are operated by long connecting rods. Necessary precautions are taken to counterbalance the weight and inertia of the mechanical system.

Where remote operation is employed, it is customary to embody an automatic dummy diagram and indicating lamps on the control board in order that the position of all breakers and isolating switches may be seen at a glance.

Busbar Selection.

One of the following four methods is generally adopted for the selection of duplicate busbars :—

(1) Air-break isolating switches for each set of bars or change-over switches—applicable to stationary gear.
(2) Change-over of plugs—applicable to draw-out gear.
(3) Oil isolators—applicable to all types.
(4) Double circuit breakers—applicable to all types.

Air-break isolating switches.—A separate set of isolators for each set of busbars is used in conjunction with a busbar coupler if the circuit has to be transferred from one set of bars to the other without breaking load.

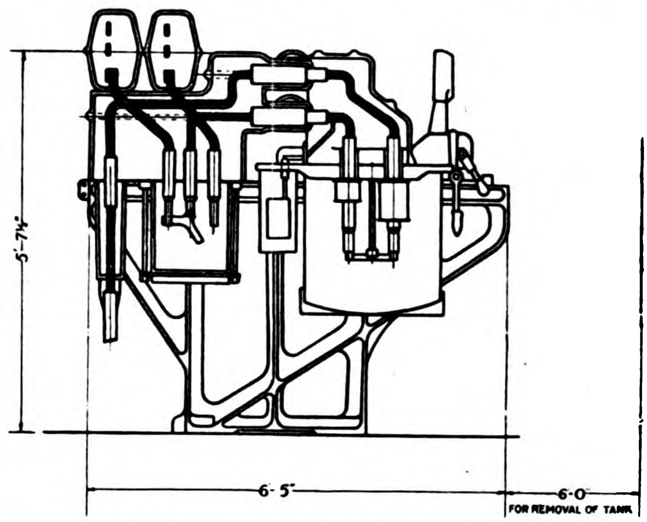


Fig. 10.—Metal-clad compound-filled switchgear unit with oil-immersed selector switches.

This can only be done with change-over switches if they are provided with double blades. Air-break isolating switches are almost universally employed on stationary gear, and in many cases the operator has to enter the switch room and expose high-tension conductors in order to operate them. This is a serious disadvantage. For convenience of connections, the two sets of isolating switches are often mounted back-to-back on opposite sides of a dividing wall, but this arrangement introduces a risk due to the possibility of incorrect operation.

Change-over of plugs.—The transfer of a circuit by this method necessitates withdrawal of the breaker, change-over of the busbar isolating plugs, of which only one set is provided, and re-insertion of the breaker. A serious objection can be raised, as an operator may change two plugs out of the three, and also a considerable time is required for transfer. It is easy to imagine how serious the inconvenience would be in the case where one set of busbars is made dead for repairs or extensions. The whole of the circuits concerned would have to be isolated and transferred one by one to the other set of bars and re-synchronized if necessary. This

scheme prevents the quick transfer of circuits in cases of emergency, and thus the main advantage of the duplicate busbar system is lost. In addition, the operator may fail to tighten the plugs in his hurry to meet an emergency.

Oil isolators.—Oil-immersed selector switches have been introduced principally for the improvement of metal-clad compound-filled gear, in order to overcome the objections already cited. The selector switches can be operated externally and are easily interlocked. Duplicate blades can be provided to allow transfer of a circuit without breaking load when used in conjunction with a busbar coupler. A unit of this type is shown in Fig. 10.

Double circuit breakers.—Although more expensive, this method is undoubtedly the best. It is almost invariably used in America on heavy power systems and is finding favour in this country on important installations.

The main advantages are:—

(*a*) All normal switching operations can be performed from the control board, giving unified control.

(*b*) Except for inspection of a circuit breaker, it is not necessary to enter the high-tension room.

(*c*) Full advantage can be taken of the facilities which duplicate busbars provide.

(*d*) One breaker is virtually a stand-by for the other, and if one is operated on a heavy fault it is possible to bring the other into service until there is an opportunity for inspection.

(*e*) It is not necessary to employ a separate busbar coupler.

(*f*) It has been suggested that with double oil circuit breakers it might be possible to transfer immediately all circuits from a faulty set of bars to the other set. Although the author is not aware that this has been done, it seems to be quite a feasible proposition.

A metal-clad switchgear unit having a double breaker in one tank is illustrated in Fig. 3. Nine terminals are provided, the middle set of three being common to both breakers.

Conclusions.

From an analysis of the fundamental features of the various types of high-tension switchgear the following conclusions can be drawn:—

Insulation.—Both compound and oil show a distinct advantage over air. The difference between compound and oil is not so marked, but the latter has advantages over the former. Oil can be used for all voltages, whereas the use of compound will probably have an upper voltage limit of 66 kV.

Isolation.—Within its range of application, the draw-out method is preferable to the stationary method. Owing to the enormous size of the apparatus and difficulty in the design of satisfactory plug-and-socket bushings, the limit of the draw-out method will probably be in the neighbourhood of 66 kV.

Enclosure.—Metal enclosure is preferable to either masonry or the open type.

Interlocks.—Complete interlocks are demanded by modern conditions and are essential both for safety and for continuity of supply.

Location.—Indoor gear is preferable for all voltages, but for 44 kV and upwards outdoor gear has an application where cost is of prime importance.

Control.—Remote electrical control is the most flexible system and for all large schemes is essential. Remote mechanical and direct control have a limited application.

Busbar selection.—Double breakers are preferable to all other methods. In the order of efficiency the remaining methods may be placed as follows: Oil isolators, air-break isolating switches and change-over of plugs.

Present-day types of high-tension switchgear combine the above features in various ways, and from the conclusions drawn it will be evident that in the author's opinion the following types are considered to be the most suitable:—

Metal-clad, draw-out, compound- or oil-insulated gear for voltages up to 66 kV.

Open floor-mounted indoor gear with separate compartments for oil breakers, for voltages of 44 kV and upwards, but outdoor gear is recommended where cost is of prime importance.

For a period, metal-enclosed air-insulated truck gear will have an application up to 22 kV, but the author believes that it will be eventually superseded by filled gear.

Section 2.

STANDARDIZATION.

Advantages and Disadvantages of Standardization.

It is unnecessary and costly to perpetuate such a large number of switchgear types as at present exist. Generating plant, transformers, motors, etc., have reached more or less standard forms, and switchgear is the only part of the equipment which can be varied to suit the individual tastes of engineers. Many take full advantage of this and, in consequence, a large number of superseded types are still specified. In addition to the types already scheduled, various supply undertakings insist on their own special variety of a particular type. Very frequently, instead of buildings being designed to suit the switchgear, the reverse is the case.

Simplification and cheapening of switchgear can be effected by standardization of the best types. Manufacturers would then be in a position to produce in bulk at a reduced cost. The price of standard types would be no more than that now paid for inferior types. In short, standardization would mean mass production, low cost, minimum of spares, and quick delivery. An objection raised to standardization is that progress would be impeded. There is little ground for this objection, because a stage has been reached where the rate of change is likely to be very much less than it has been in the past.

The creation of new designs has been prolific and it is now necessary to consolidate the position so that the perfection of the best types may lead to their general adoption and production in such quantities as to reduce the cost and benefit the whole industry.

Relation of Cost to Standardization and Quantity Production.

The cost of central station switchgear varies from about 3 per cent of the overall capital cost in the case of stations round 20 000 kVA, to about 6 per cent in the case of super-power stations. Central station switchgear is a vital part of the system, and it is unwise to adopt a "cheese-paring" policy in relation to it.

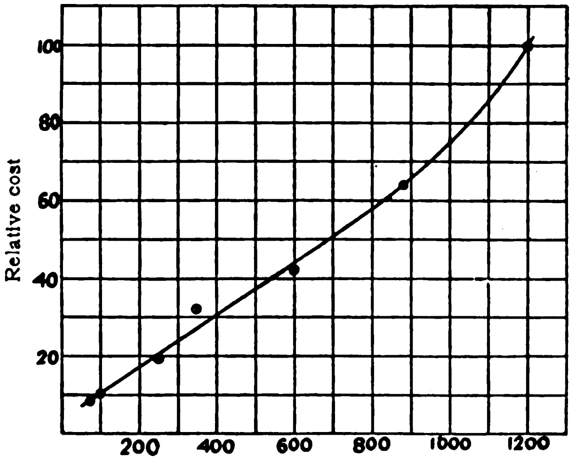


Fig. 11.—Relation of cost to breaking capacity.

It is an inherent disadvantage of the a.c. method of distribution that the cost of switchgear increases rapidly with the size of the system, and hence switchgear accounts for an appreciable portion of distribution costs.

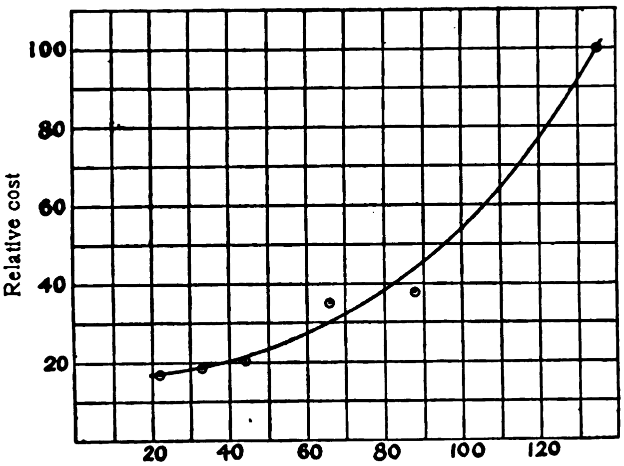


Fig. 12.—Relation of cost to rated voltage.

This fact has led many engineers to reduce considerably the factor of safety as regards the breaking capacity of substation switchgear, and it has been suggested that, when cables and transformers, etc., are more immune from breakdown, it may be possible to cut down switchgear equipments by the solid connection of apparatus. In the author's opinion, a much more fruitful course to pursue would be the reduction of cost by standardization, without any sacrifice of flexibility of control and continuity of supply.

The cost of switchgear for high-tension generating voltages is a function of its breaking capacity, as indicated by the curve shown in Fig. 11.

For pressures up to 1 000 volts the cost usually varies with the normal current rating, whereas for extra-high voltages the predominant factor is the rated voltage, as illustrated in Fig. 12.

The manufacture of switchgear demands a proportionately larger staff than any other manufacturing branch of the electrical industry. Purchasers will accept standard machines or transformers, but by reason of special requirements and conditions they make switchgear more expensive than it need be. In British switchboard factories the annual cost of the drawing office is 70 to 80 per cent of the productive labour costs for the assembly of switchboards. This is not surprising, since there are scarcely two switchboards alike. The advent of standardization would reduce overhead charges and labour costs. This tendency is illustrated in Fig. 13, which relates to a special variety of a certain type of switchgear standardized by a supply authority. Curves A and B show how the overhead charges and labour costs decreased as more orders for this particular gear were executed. The predominant factors were the reduction in drawing office expenditure and the increased familiarity of workmen with the standardized product. Curve A gives the relative total

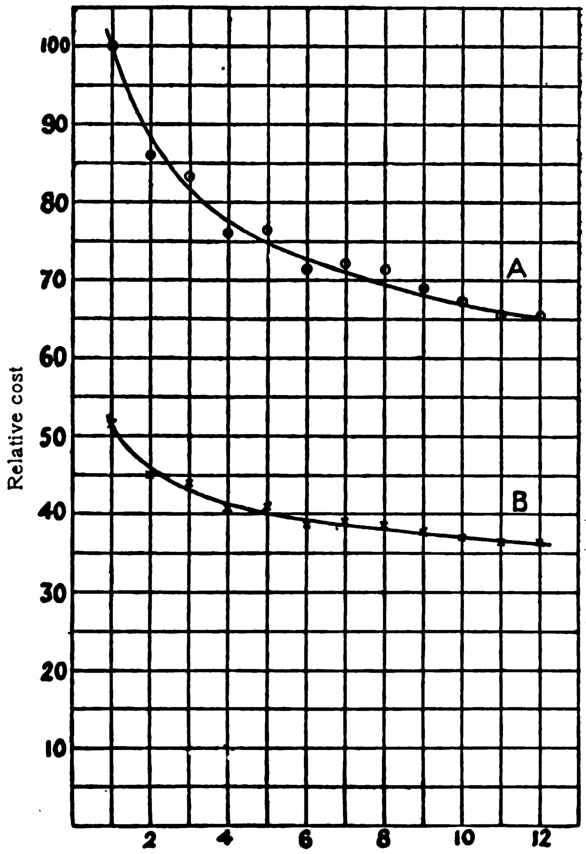


Fig. 13.—Reduction of cost by standardization.

factory cost, and curve B indicates the relative cost of material plus labour. The cost of material may be taken as being approximately constant.

Jigs and tools for production at low cost, provision of interchangeability, and elimination of the human element are only warranted if there is a sufficient demand for the product. As is well known, it is the quantity produced which determines the price of a standard product.

It is the standardization of type which is most important, because variations in circuit equipments, protective gear, etc., can be made without materially increasing the cost. At the present, mass production cannot be applied to switchgear owing to the multiplicity of types and the consequent limited demand for each.

Types Recommended for Standardization.

If suitable types are to be standardized it is essential that they shall consist of factory-built units in order that mass production may be possible. The vital question as to which types shall be chosen can only be answered by the pooling of experience gained by supply undertakings in the operation of existing types. It would certainly be dangerous to standardize prematurely, but the author feels confident that the demand is in the ascendancy for those types embodying the draw-out feature and filled insulation. Both features have been tried out during the past 20 years with increasing satisfaction to the users. Several of the leading manufacturers in this country have recently put such types on the market, necessitating a heavy outlay in patterns, jigs and tools, which in itself indicates that the demand is likely to increase. American and Continental engineers also have recently taken a keen interest in this distinctively British development and have been exploring the possibilities of taking up manufacture in their own countries.

It is certain that the factors which brought this form of gear into existence, namely, space considerations, demand for stability of insulation, protection to life and low cost, will continue to operate, and the best types should ultimately prevail.

Since mass production and cost are inseparably bound up with each other, low cost will not be attained until the gear is standardized and made the prevailing type. It is a common fallacy to associate metal-clad draw-out gear with high initial cost. Even with its limited application to-day the cost is usually not more than 10 per cent above that of other types.

The author confidently believes that, within their range of application, the types which will ultimately be standardized will be in the form of metal-clad, fully interlocked, draw-out, compound- or oil-filled gear.

Section 3.

SCHEMES OF CONNECTIONS.

In planning a scheme of connections for any large power system it is possible to get numerous combinations, and this section deals with the many variables which enter into the problem.

Arrangements of Main Busbars.

The main busbars of a central station may be arranged according to the different systems enumerated :—

(*a*) Single.
(*b*) Single ring.
(*c*) Duplicate.
(*d*) Duplicate ring.
(*e*) Sectionalized.

(*a*) *Single busbar system.*—A single set of busbars is now rarely employed in central stations, because work on the bars or connections thereto cannot be carried out without interruption of the supply. They are, however, frequently used in substations where the bars can be occasionally made dead.

(*b*) *Single-ring busbar system.*—A single-ring busbar arrangement is indicated in Fig. 14. The ring formation renders it possible to disconnect any section for alterations and repairs.

Single-ring busbars have an obvious disadvantage in that the generators and feeders on the disconnected section need to be made dead. This is rarely possible under modern conditions unless the feeders are inter-

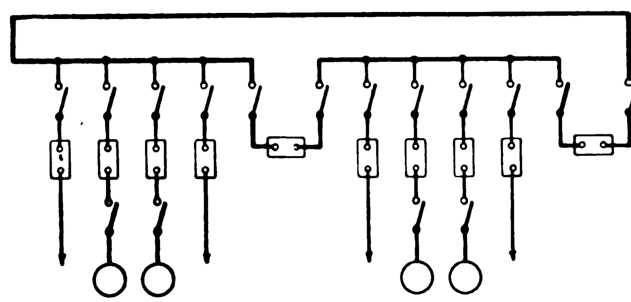


Fig. 14.—Single-ring busbar system.

connected outside the generating station in such a way that they can be fed by an alternative route. The advantage of single-ring busbars lies in the fact that one set of isolators only is required for each circuit.

(*c*) *Duplicate busbar system.*—It is now almost universal practice to provide a duplicate set of busbars in central stations, as it enables a supply to be maintained even if there should be a fault on one section of the bars. Fig. 15 shows a duplicate busbar system.

Spare plant is usually provided in any generating station, and it is obviously necessary to provide spare busbars if continuity of supply is to be maintained. Not only do the spare bars serve as a stand-by but they are used frequently to facilitate control of the system. The main advantages are scheduled below :—

(i) Cleaning, repairs or extensions to busbars are possible without interruption of the supply.
(ii) Certain feeders can be worked under conditions differing from the remainder, e.g. voltage boost at times of heavy load.
(iii) A supply from an interconnected generating station can be received and distributed without running in parallel.

(iv) A feeder which has been under repair can be tried out separately with a spare machine before paralleling with the rest of the system.

(v) Non-adjacent busbar sections which are lightly loaded can be paralleled through the spare bars and run as one section.

(vi) A feeder supplying a faulty overhead line can be put on the spare bars and connected to an alternator, which is isolated from the rest of the system. The faulty phase would be earthed at the station and the supply maintained until an opportunity occurred to repair the line.

In order to take full advantage of the duplicate busbar system, it is necessary to provide means for synchronizing and paralleling the two sets of bars so as to enable circuits to be transferred without breaking load. Where control is by single breakers it is necessary to provide a separate busbar coupler for each section, as shown at Y (Fig. 15). Where duplicate breakers are used, this coupler is unnecessary.

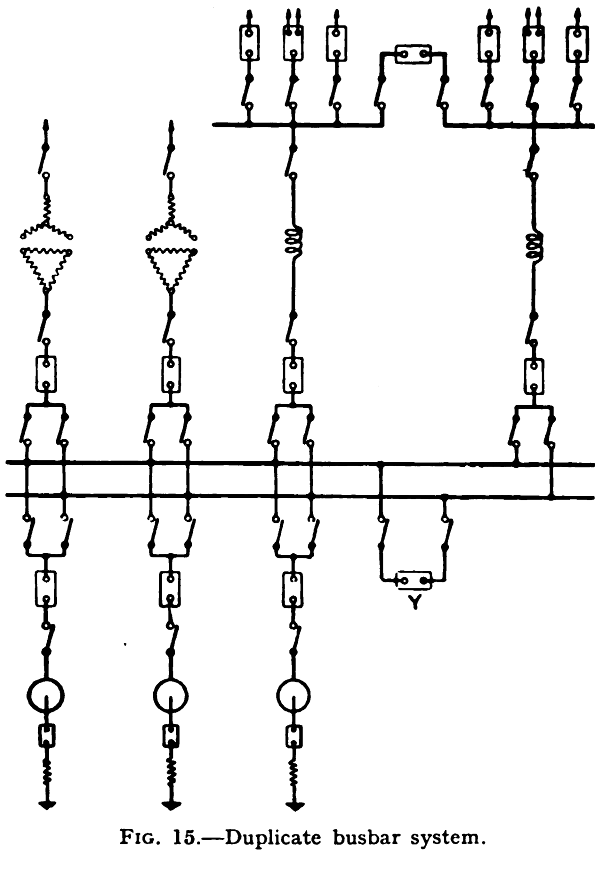


FIG. 15.—Duplicate busbar system.

(*d*) *Duplicate-ring busbar system.*—This system consists of duplicate busbars in ring formation. Supply can be maintained even though a section of the main bars as well as a section of the spare bars is disabled, provided the two faults are on different busbar sections. The duplicate-ring arrangement is shown in Fig. 16.

(*e*) *Sectionalized busbar system.*—For super-power stations the busbars are almost invariably divided into sections, each controlling 20 000 to 40 000 kVA of plant. With this arrangement the generating plant can be sectionalized at times of full load; the short-circuit current which may flow into any fault is reduced and the effects of a disturbance are limited. Sectionalization also provides suitable points for the insertion of reactors, when required. It is necessary to watch that interconnected feeders outside the generating station are fed from the same busbar section.

Facilities for synchronizing and coupling any two busbar sections should be arranged. For adjacent sections a busbar section switch is provided, as shown at X (Fig. 20); other sections can be coupled together through the busbar couplers and spare bars.

Methods of Busbar Selection.

This question has been dealt with in Section 1. Single breakers and selector switches are shown in Fig. 15.

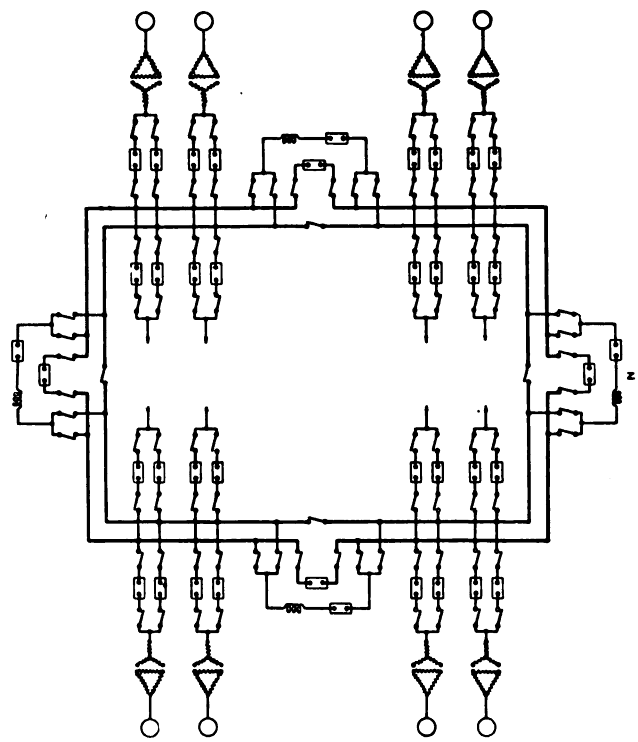


FIG. 16.—Duplicate-ring busbar system.

Where double breakers are used they are so interlocked that normally both cannot be closed at the same time. The interlock can be removed if it be desired to parallel the duplicate bars. Selection by means of double breakers is illustrated in Fig. 16.

Busbar Reactors.

Some form of reactance is essential in modern super-power stations, where the peak short-circuit currents may exceed 100 000 amperes. The electromagnetic forces and heating vary as the square of the current, with disastrous effects if the short-circuit power is not limited.

Reactance may be inserted in generator, feeder or

busbar circuits, and in America all three methods are used, whereas the most usual British practice is to employ busbar reactance only. The latter is installed at points where there is little transfer of energy under normal load conditions, but where, unless limited by reactance, large amounts of power would flow under fault conditions. The voltage-drop across the reactor under normal conditions is thus reduced, and consequently a higher value of reactance can be employed.

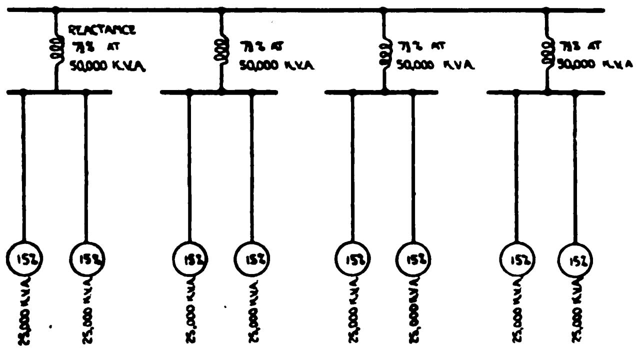


FIG. 17.—Star-connected busbar reactors.

In the case of feeder and transformer circuits it is preferable so to arrange them that the maximum amount of inherent impedance is obtained. This may be done by sectionalizing parallel feeders, with a consequent reduction in the short-circuit current. Reactors are necessary, quite apart from the reduction in breaking capacity of switchgear. Oil circuit breakers can be built to interrupt practically any value of short-circuit power, but it is preferable to limit the latter because,

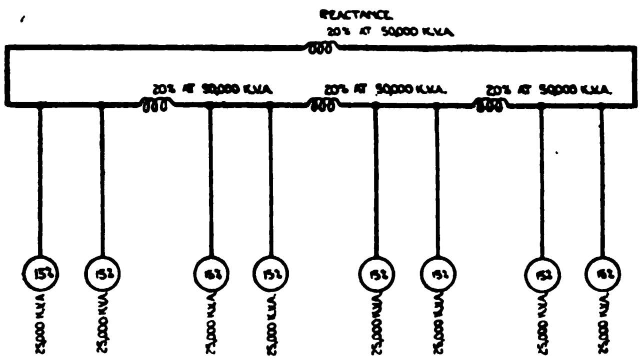


FIG. 18.—Ring-connected busbar reactors.

before the breaker can operate, severe stresses are imposed on the system although the breaker itself may be undamaged.

Two arrangements of busbar reactance are in common use, namely :—

(1) Star system (see Fig. 17).
(2) Ring system (see Fig. 18).

The advantages and disadvantages of these alternative methods have been dealt with by E. B. Wedmore.*

Feeders which are interconnected outside the generating station must be fed from the same busbar section, or otherwise they will short-circuit the busbar reactor. It is possible to provide means for automatically short-circuiting the reactor on each side of a busbar section if the alternators are disconnected or transferred.

The use of busbar reactance enables the short-circuit power of large stations having 200 000 kVA plant capacity to be limited to 750 000 kVA, with satisfactory voltage regulation. Fig. 17 shows a scheme for a station of this size with star-connected busbar reactors. The maximum short-circuit power is limited to approximately 650 000 kVA, and the voltage difference between sections need not exceed 2 per cent at 0·8 power factor.

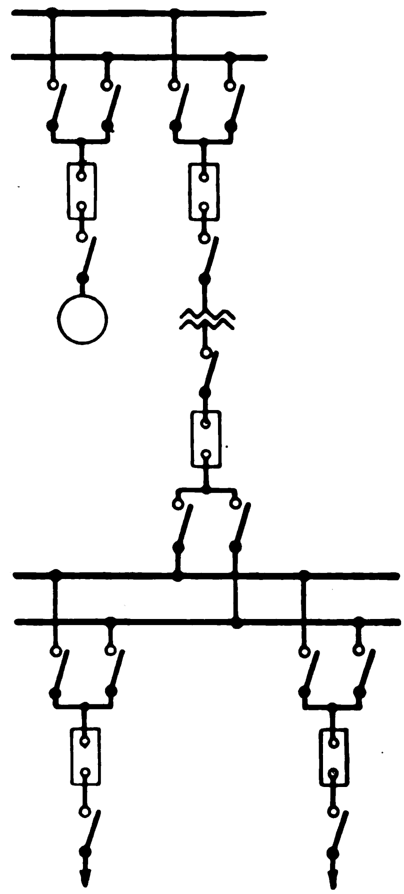


FIG. 19.

A similar scheme with ring-connected busbar reactors is shown in Fig. 18, and in this case the maximum short-circuit power is again limited to approximately 650 000 kVA.

The cost of reactors is usually less than the cost of switchgear of higher breaking capacity, where there is a large number of circuits. It is sometimes urged that the addition of reactance increases the duty on the breakers, but it should be borne in mind that the most severe faults are those near the generating station and the power factor is very low, so that the addition of reactance reduces the fault current with little alteration

* "Control of Large Amounts of Power," *Journal I.E.E.*, 1918, vol. 56, p. 269.

to power factor, the duty on the breaker being consequently reduced by a considerable amount.

Ring-connected busbar reactors should each be provided with a breaker connected in series for interrupting the load when the reactor is in circuit, and one connected in parallel for short-circuiting the reactor. The necessary isolators should be included as shown at Z (Fig. 16). For star-connected reactors it is necessary to provide one series breaker together with isolators, as shown at W (Fig. 20).

Methods of Control.

In many modern stations the voltage has to be stepped up for transmission, and in some cases power is also distributed at the generating voltage.

The following are alternative methods of control:—

(*a*) Alternator, transformer and feeder controlled separately.
(*b*) Alternator and transformer switched as one unit.
(*c*) Transformer and feeder switched as one unit.
(*d*) Alternator, transformer and feeder switched as one unit.

(*a*) *Alternator, transformer and feeder controlled separately.*—This arrangement is shown in Fig. 19, and the following are its advantages and disadvantages.

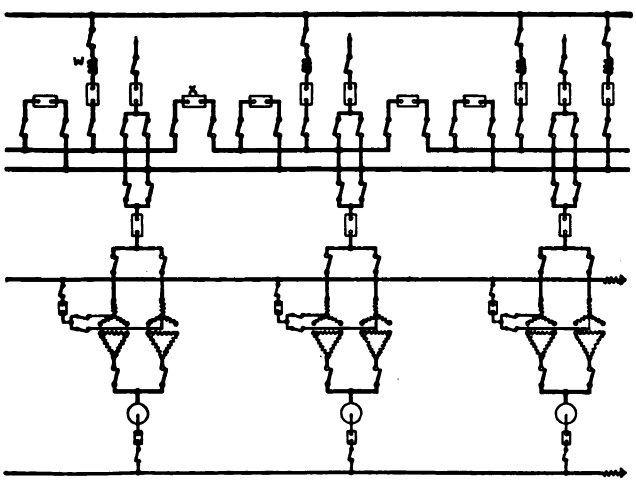


Fig. 20.

Advantages :—

(i) Plant can be operated at its maximum efficiency, because any unit can be disconnected when not required.
(ii) Breakdown on any one unit does not affect the remainder.
(iii) Discriminative protective gear can be provided on the transformers and alternators separately.
(iv) All transformers can be made the same size, so that a minimum number of spares are necessary.
(v) Where transmission is at two or more voltages this method enables all generators to supply any feeder if required.
(vi) The capacities of the alternator, transformer and feeder need not be definitely related.

Disadvantages :—

(i) High cost.
(ii) Heavy transients are possible when switching-in transformers and feeders.
(iii) The grouping of generators gives higher short-circuit current than would obtain if they were connected in series with the transformers.

(*b*) *Alternator and transformer switched as one unit.*—Fig. 20 indicates this scheme, which has the following advantages and disadvantages.

Advantages :—

(i) Low cost, as heavy-current switching is eliminated.
(ii) The magnitude of short-circuit currents is reduced due to the transformer impedance.
(iii) The transformer is magnetized gradually, thus eliminating heavy transient currents, which ordinarily occur with separate switching.
(iv) Separate breakers are retained on feeder circuits, as these are most liable to be called upon to operate frequently.

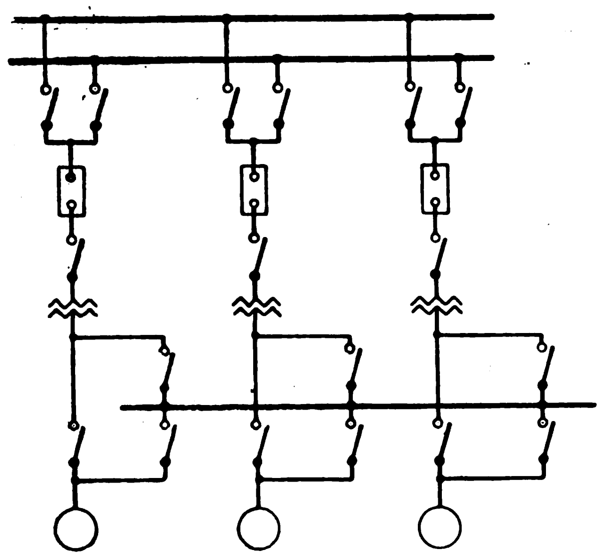


Fig. 21.

Disadvantages :—

(i) The transformer and alternator must be of equal capacity.
(ii) A faulty alternator on one set and a faulty transformer on another set may put two equipments out of action unless a transfer bar, as shown in Fig. 21, is provided.

With this scheme, three-phase power transformers corresponding to the generator capacity would be very large, and occasionally they are connected in parallel, as indicated in Fig. 20. The neutral points of the machines may be coupled together under normal running conditions and earthed, with consequent simplification of neutral switching equipments. This differs

from the usual practice of only earthing the neutral poiht of one machine at a time, as in this case the machines are not interconnected electrically except at the neutral point.

(*c*) *Transformer and feeder switched as one unit.*—Common control of transformers and feeders is illustrated by Fig. 15. The advantages and disadvantages are :—

Advantages :—

(i) Switching surges on the high-tension side of the transformer are reduced to a minimum.
(ii) The transformer introduces reactance between the busbars and feeder so that a fault on the latter has the minimum effect on the system voltage.
(iii) No super-tension breakers are required.

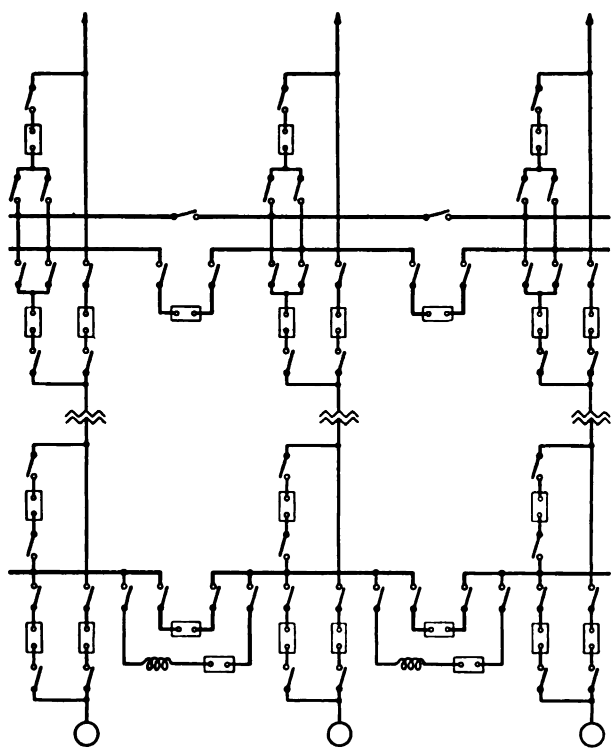


FIG. 22.

Disadvantages :—

(i) The transformers have to be of varying capacities to suit different feeders.
(ii) The failure of a transformer puts its feeder out of commission until repairs can be effected. Transfer bars would overcome the difficulty.
(iii) In the case of feeders paralleled at the receiving end, the opening of one transformer breaker causes a larger voltage-drop on the other feeders than would be the case with other methods of connection.
(iv) The overload capacity of an overhead feeder is very much greater than that of a transformer, but this advantage cannot be utilized if transformer and feeder have equal capacities.

(*d*) *Alternator, transformer and feeder switched as one unit.*—Where heavy blocks of power have to be transmitted at very high voltages it is often necessary to switch the alternator, transformer and feeder as one unit. Such a scheme is indicated in Fig. 22.

The advantages and disadvantage are :—

Advantages :—

(i) Switching surges are reduced to a minimum because the voltage is gradually applied to the transformer and line.
(ii) The system is independent of busbars for normal running.
(iii) The short-circuit power is reduced to a minimum.

Disadvantage :—

(i) The failure of one unit renders a group inoperative unless main busbars or transfer bars are provided, as shown in the figure.

Group switching.—Where there are a large number of outgoing feeders, it becomes very expensive to provide circuit breakers each capable of dealing with the maximum short-circuit power, and group feeder control is often adopted in order to reduce the cost. A scheme embodying this method is shown in Fig. 15; sometimes a reactance is connected in series with each group breaker, as is the case in the scheme illustrated. Each group breaker has sufficient breaking capacity to deal with the maximum short-circuit power, whereas the individual feeder breakers are arranged to deal with only a proportion thereof. The former is usually set at a high value for instantaneous tripping and clears short-circuits, whilst the latter are usually provided with a lower setting having a fixed time-lag and deal with ordinary overloads. A failing of this scheme is that a dead short-circuit on one feeder will cause the whole group to be disconnected. An alternative arrangement sometimes adopted is shown in Fig. 23.

The opening of the group breaker introduces a reactance of such a value that the short-circuit power is reduced to an amount within the capacity of the feeder breakers, and the former is set to operate at a predetermined value of short-circuit current approaching the safe limit of the smaller breakers. A value of reactance is chosen such that considerably more than half the breaking duty is imposed on the group breaker. Obviously, this modification enables a fault on one feeder to be cleared without interference with the rest, and the group breaker does not disconnect the circuit but merely removes the short-circuit from the reactance.

SUBSTATION SCHEMES.

The scheme of connections for a substation is usually much simpler than that for a central station, and flexibility of control is frequently sacrificed in order to reduce the initial cost.

Where the busbars can be occasionally made dead, the single-busbar system is adopted. In order to keep one half in commission whilst the other half is made dead, the busbars are often split into two sections by an isolating switch or non-automatic breaker. Duplicate bars are resorted to in important substations.

It should be remembered that, with the ring-main system of feeders, the substation busbars form part of the ring, and a fault on these may involve the supply to other substations. The scheme of connections to be adopted in any particular case will vary according to the type of feeders used and also whether discriminative protective gear is employed. Supply engineers are constantly in search of methods for the reduction of substation switchgear costs by the elimination of automatic control on certain units of the plant or by controlling two units by one breaker, e.g. a dead-ended substation supplied by a radial feeder and equipped with one transformer may be controlled by one breaker; a similar substation supplied by duplicate radial feeders may be controlled by two breakers. In such cases, however, flexibility is sacrificed because difficulties would arise if a second transformer had to be installed or the supply fed into the substation from two directions.

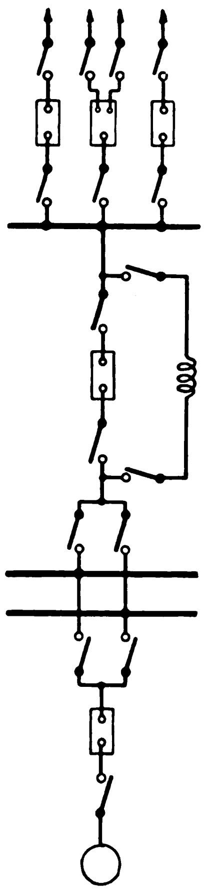


Fig. 23.

On some schemes the complete plant is divided into two sections both at the central station and at the substation, each large substation being fed by duplicate feeders, one on each section. The feeders and transformers are controlled by two automatic breakers in the substation, so arranged that only one can be closed at any one time; thus the consumer has two alternative supplies.

If discriminative protective gear is not used on the feeders, they are occasionally coupled solid and protected at the generating station only, and this is occasionally adopted on underground cables working at generating voltages, where a high degree of reliability has been attained. In this scheme a fault on the cable would affect all consumers fed from the ring main.

It will be evident that any departure from separate automatic control of each unit introduces disadvantages which might be more costly to the supply authority during the life of the switchgear than the initial outlay on the full equipment.

Substation fed by ring mains.—One of the most frequent problems encountered by supply engineers is how to deal with switchgear in substations where an incoming and outgoing cable form part of a ring main and a consumer's transformer has to be controlled. Fig. 24 gives four alternative arrangements.

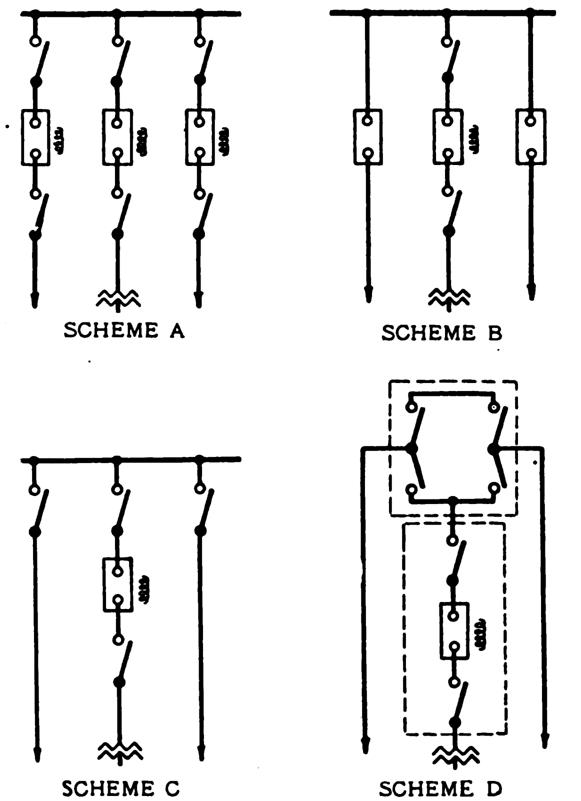


Fig. 24.

The best and most generally adopted arrangement is shown at A, in which separate automatic control is provided for each unit. Where the feeders are not fitted with discriminative protective gear the feeder breakers may be replaced by non-automatic breakers, as indicated at B. A further reduction in cost can be effected by the provision of isolators only on the ring-main feeder, as illustrated at C. An arrangement which allows the ring main to be kept closed while the substation bars are made dead is given at D.

It is important that the ring main should be kept closed under all conditions, and from arrangement D it

will be seen that the isolators have double blades which enable the substation board to be disconnected without opening the ring. Schemes C and D require very careful manipulation and only skilled attendants can be employed. For scheme C, before the isolators are opened it is necessary to ascertain whether the ring is broken at any other place, either at the generating station or at any of the substations. If a break should exist and the isolators were operated, then the latter would break load current at full voltage; whereas, with a closed ring, current would only be broken at a voltage represented by the potential difference at both ends of the ring where opened, say, a maximum of 200 to 300 volts. Skilled attendants operating the isolators quickly under these conditions have been able to avoid trouble, but the risk is always present.

The provision of voltage indicators on feeders is helpful in determining whether the ring is closed or otherwise. It will be evident that the ring may be opened automatically at the same instant that an attendant is opening the isolators, so that danger cannot be entirely eliminated. During these operations the out-of-balance relays must be rendered inoperative on the ring main because the isolators are not opened simultaneously.

without interfering with the supply to any consumer. Such an arrangement is not practicable with the remaining three schemes, and a fault on any section will

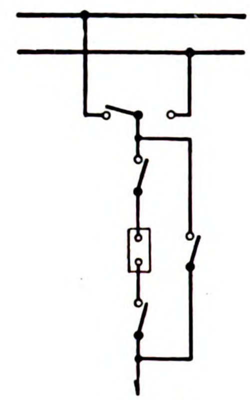


FIG. 25.

interrupt the supply to the whole of the consumers on the ring.

(2) *Continuity of supply.*—Any section can be opened up for inspection or repair without interfering with the

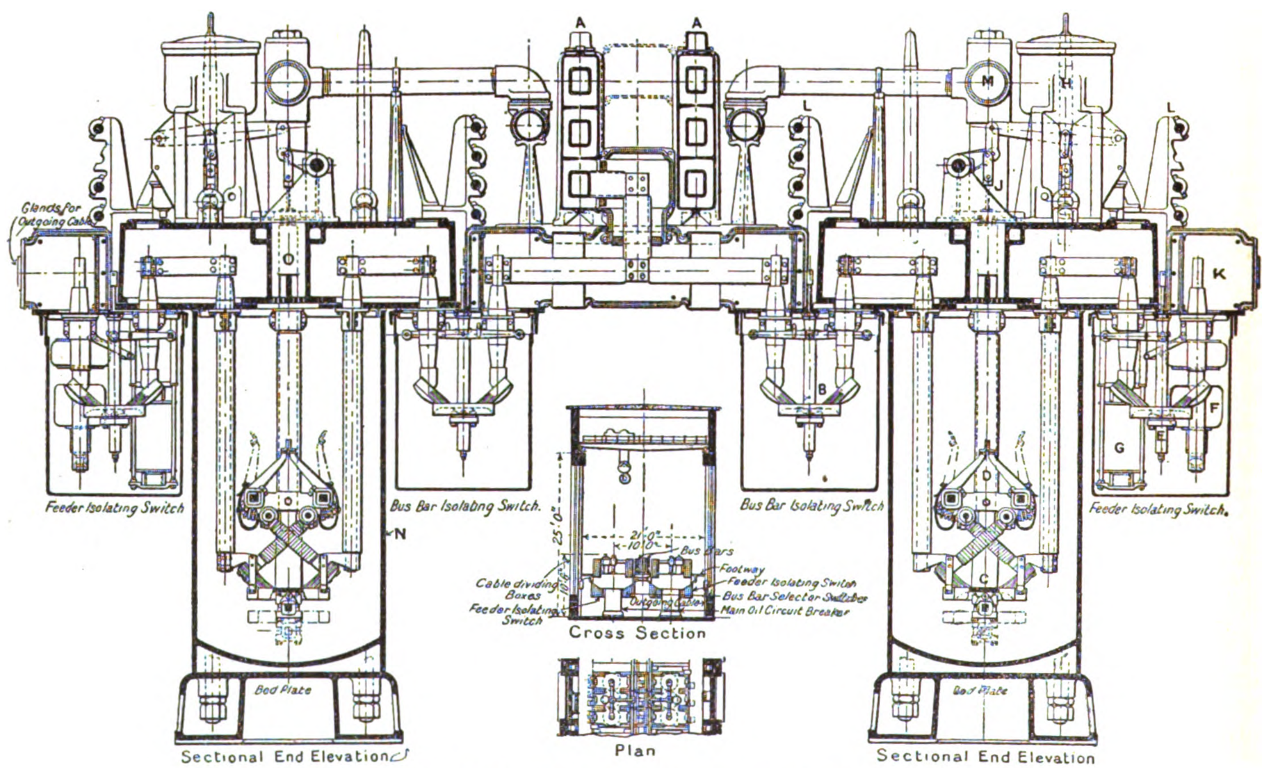


FIG. 26.—Heavy-duty metal-clad compound-filled switchgear unit.

ADVANTAGES OF SCHEME "A" OVER SCHEMES "B," "C" AND "D."

(1) *Protection.*—It is possible to provide discriminative protective gear for each section of the ring main so as automatically to isolate any faulty section at both ends

supply to the consumers. This is also possible with scheme "B," but is more difficult with schemes "C" and "D."

(3) *Maintenance.*—The minimum amount of time is required for the isolation of a faulty section and the

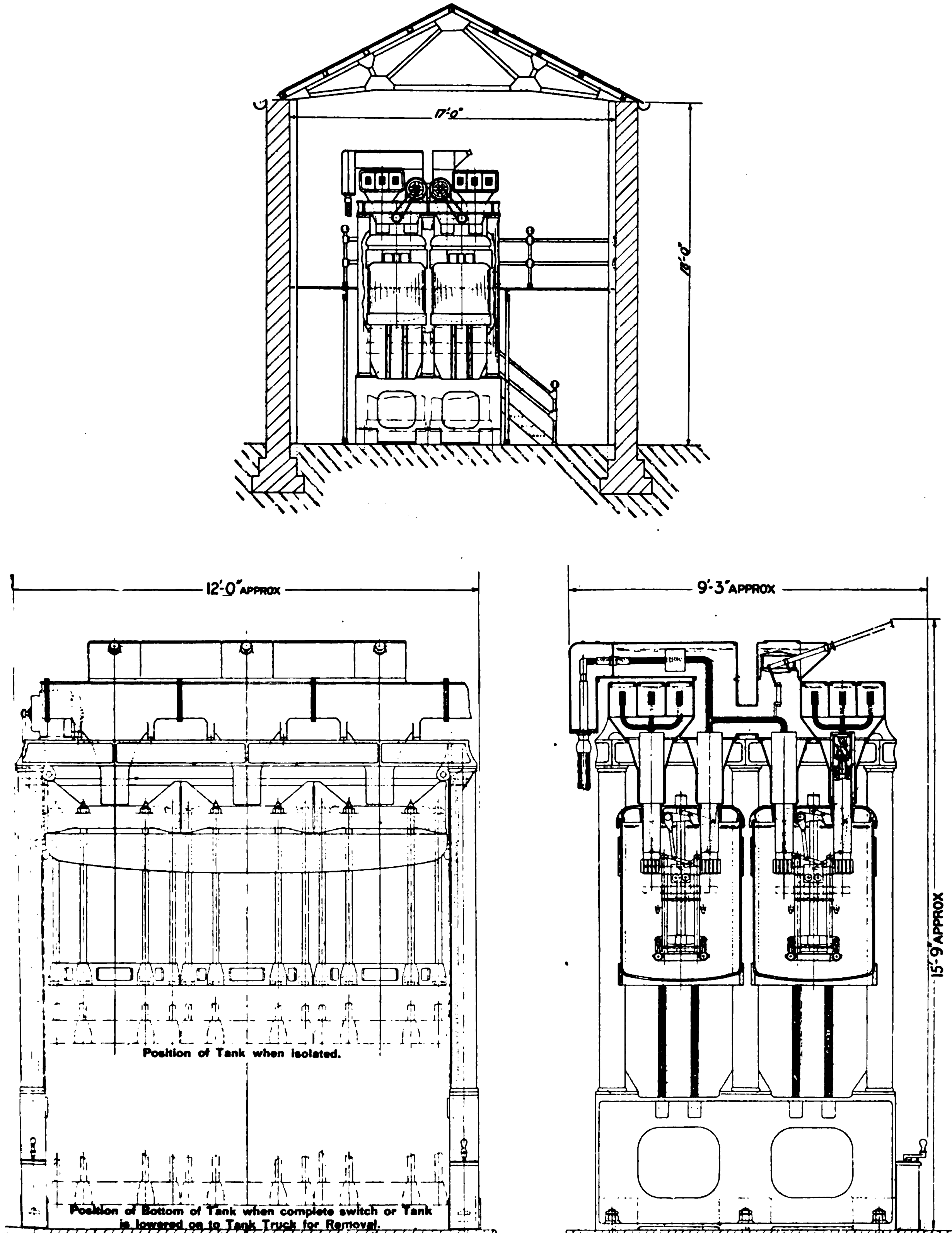


Fig. 27.—Heavy-duty metal-clad compound- or oil-filled switchgear unit, with double breakers.

localization of the trouble, i.e. there is the least period of interruption of the supply. If the ring has been opened automatically by a fault, the supply can be quickly resumed by telephoning to the substation concerned. This is possible with arrangement "B," but it is not so with arrangements "C" and "D," because it is necessary for the mains engineer to visit the substation in order to localize and isolate the faulty section.

(4) *Reliability*.—Several breakers are provided on the ring main, and thus there is less dependence on the generating station breakers. In the case of schemes "B," "C" and "D" there is no second line of defence.

Advantages of Scheme "D" over Scheme "C."

(1) *Isolation of substation busbars*.—The supply to other substations is not jeopardized, because the busbars can be made dead without breaking the ring. With scheme "C" not only is the ring opened but before the busbars can be made dead it is necessary to ascertain whether the ring is opened or not at any other place, and to render any balanced relays inoperative.

shut-down. There is not the same facility and security with scheme "C."

It will be evident that scheme "A" affords con-

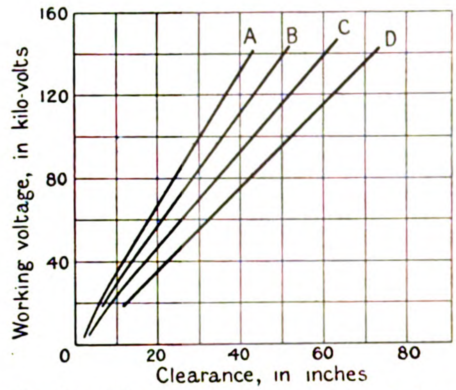


FIG. 28.—Clearances for conductors, indoor and outdoor.

siderable advantage over the others, but where capital cost is the first consideration it is possible to employ

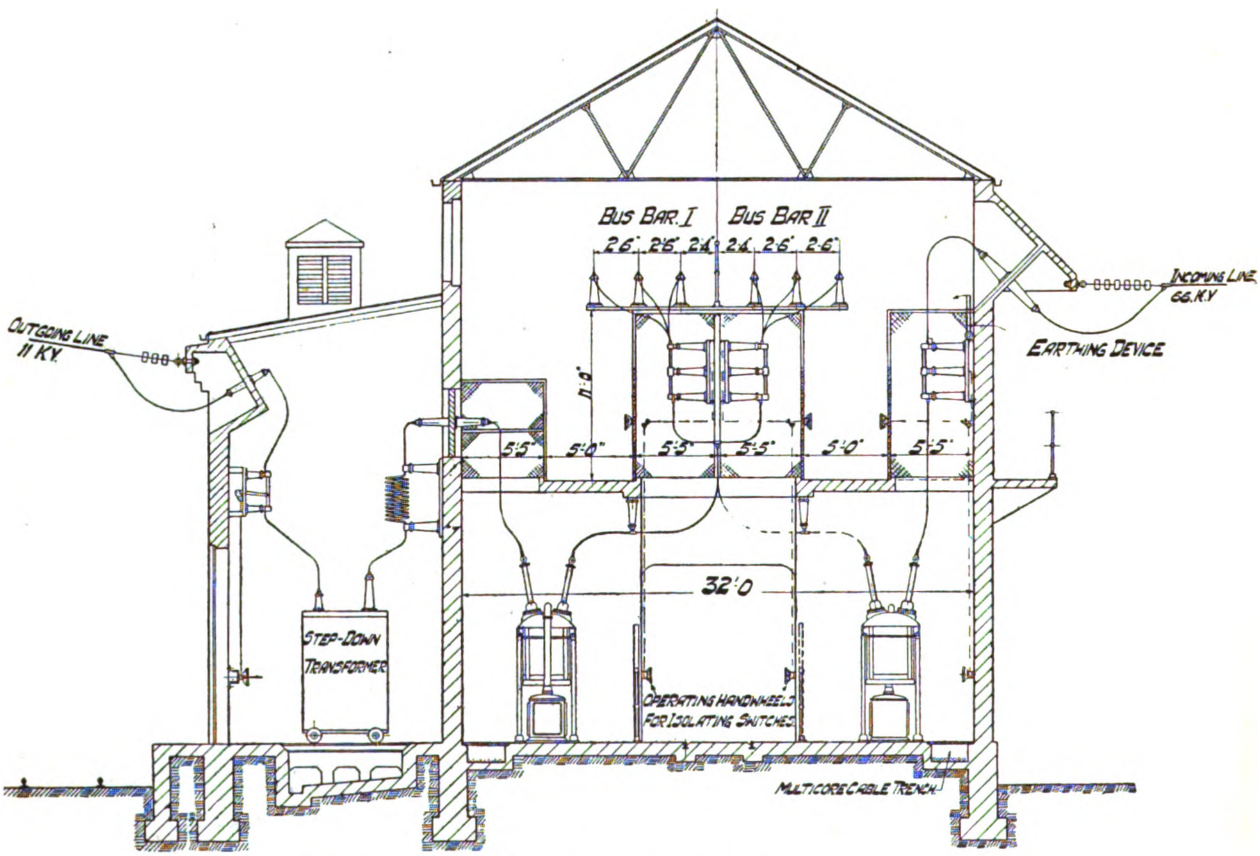


FIG. 29.—Layout of 66-kV indoor station. Sectional elevation.

(2) *Isolation of section of ring main*.—When it is desired to isolate sections of the ring main, a consumer can be transferred from one section to another without

scheme "A" at the important substations and one of the other schemes at the less important substations on the same ring main. Schemes "B" and "C" may be

incorporated in a single metal-clad draw-out type unit having oil-immersed isolators, as illustrated in Fig. 10.

General Considerations.

Isolators.—Isolators should be provided on each side of oil circuit breakers. In some cases they are omitted from the side of the breaker remote from the busbars, but it is very dangerous practice and fatal accidents have occurred on account of this omission. It is imperative that there should be no fear of the breaker being made alive from the other end, and the attendant should be able to see for himself that the breaker is isolated on both sides.

Single-pole isolating switches cannot be relied upon to break any current but, where the poles are coupled and remotely operated, the magnetizing current of small transformers or the charging current of short transmission lines may be broken.

Difficulty occasionally arises with protective gear when pole-operated isolators are operated consecutively, on account of the unbalanced capacity currents which affect core-balance protection, and hence mechanically-operated isolators are now frequently used.

Potential transformers.—It is highly desirable to avoid the connection of potential transformers to the busbars, because the former are a very weak link in the system. It is better to connect them to the individual circuits on the side of the breaker remote from the busbars, and all ordinary synchronizing operations can still be carried out. The synchronizing of busbar sections or main and spare bars can be carried out by the use of potential transformers on the machines connected to the individual sections or sets of bars. Difficulties arise if summation wattmeters are required, and if potential transformers must be connected to the busbars they should preferably be protected by an oil circuit breaker.

Synchronizing.—Interlocks are occasionally provided to prevent generators being connected to the busbars before the synchronizing instruments have been energized. This is accomplished by the provision of auxiliary contacts on the synchronizing plug. These complete the control circuit of the electrically-operated breaker, so that the latter cannot be closed until the synchronizing instruments are in circuit.

By-pass switches.—On super-tension systems, where a considerable time would be required to carry out the inspection of a breaker, a by-pass switch is often used, as shown in Fig. 25. Its function is to short-circuit the breaker so that the latter can be taken out of the circuit without opening the line connections.

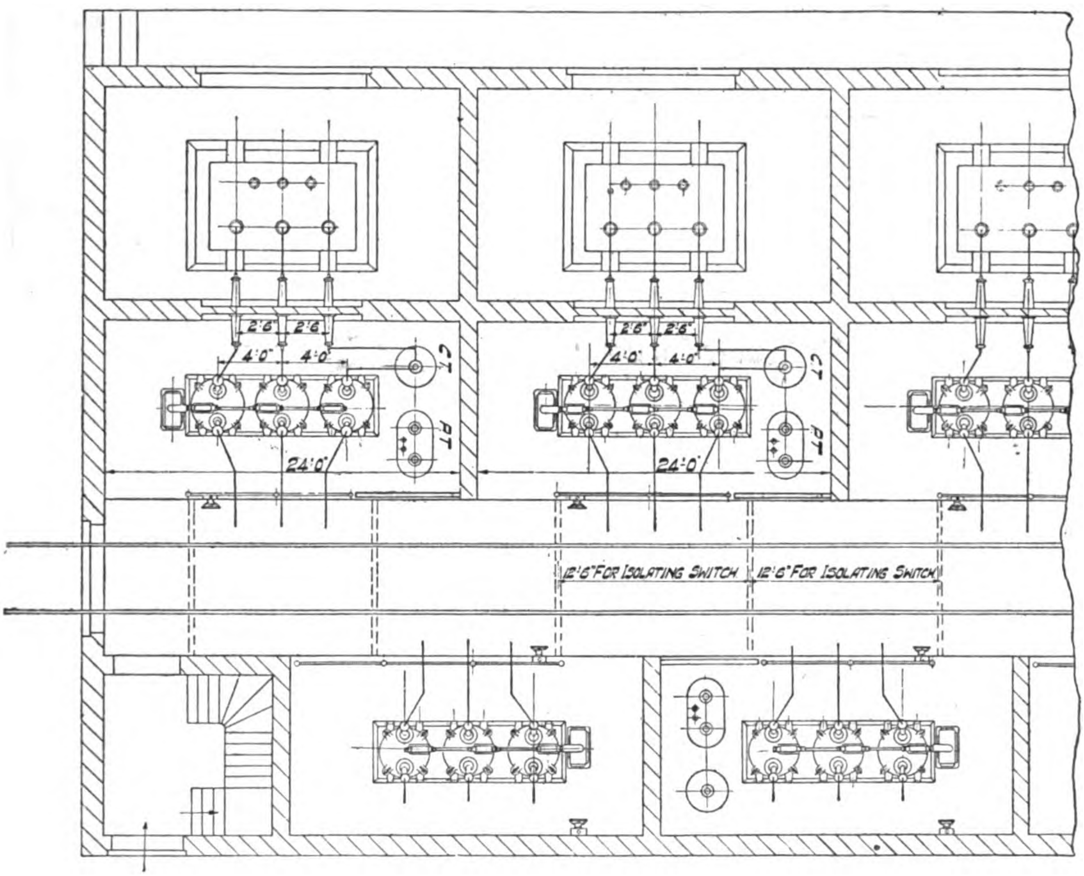


Fig. 30.—Layout of 66-kV indoor station. Plan.

Section 4.

TYPICAL INSTALLATIONS.

Installations operating at high-tension generating voltages are generally well known, but, as an example of modern super-power station switchgear, two illustrations of the metal-clad type are included.

overhead crane, thus exposing the internal portions of the breaker.

A metal-clad compound or oil-filled switchgear unit of the vertical draw-out pattern is illustrated in Fig. 27. Double breakers are provided for busbar selection, and each set is raised and lowered separately by means of a motor-operated mechanism.

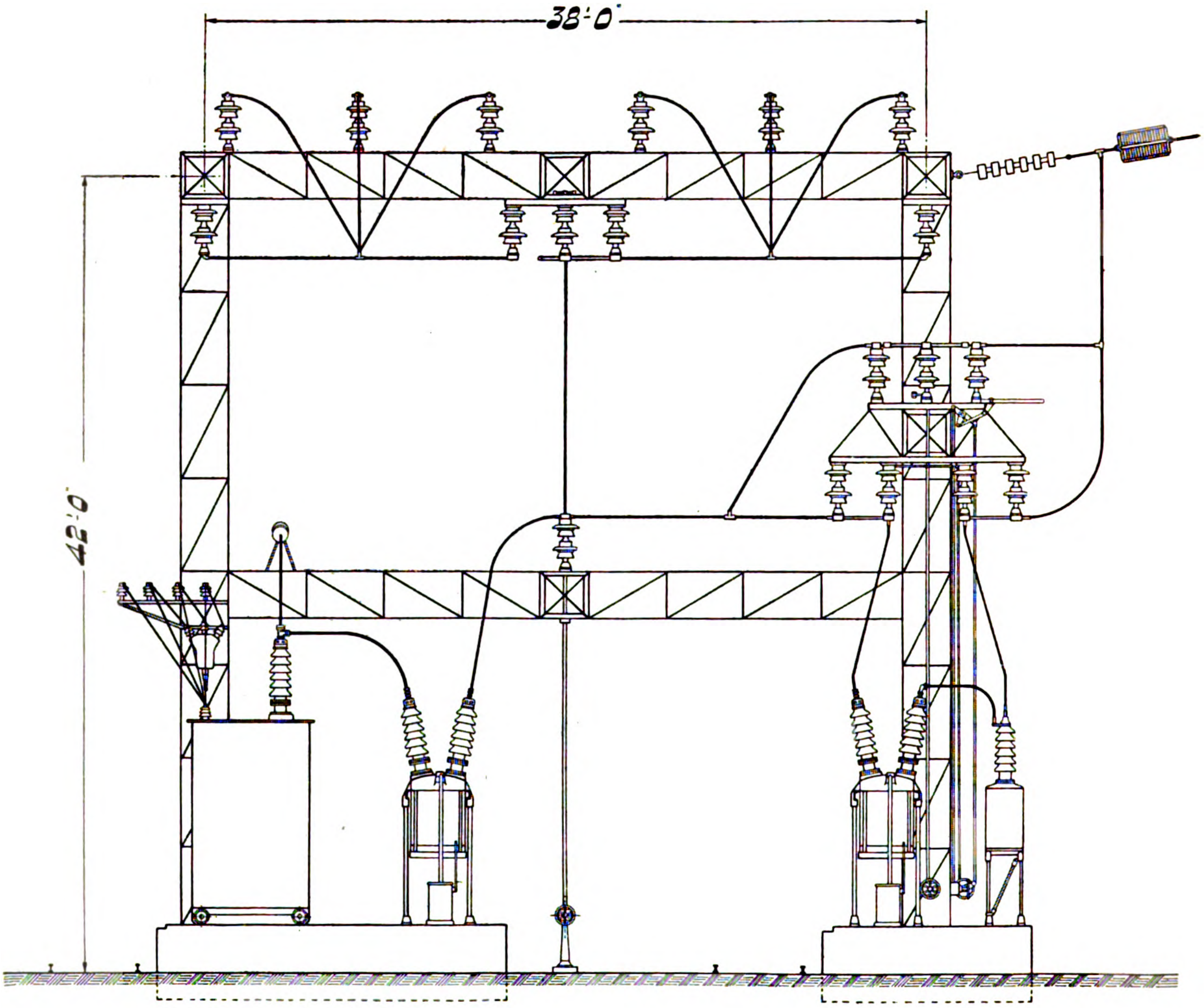


Fig. 31.—Layout of 66-kV outdoor station. Sectional elevation.

Super-tension schemes are not so generally well known, and accordingly a number of typical indoor and outdoor layouts are given.

Super-Power Station Switchgear.

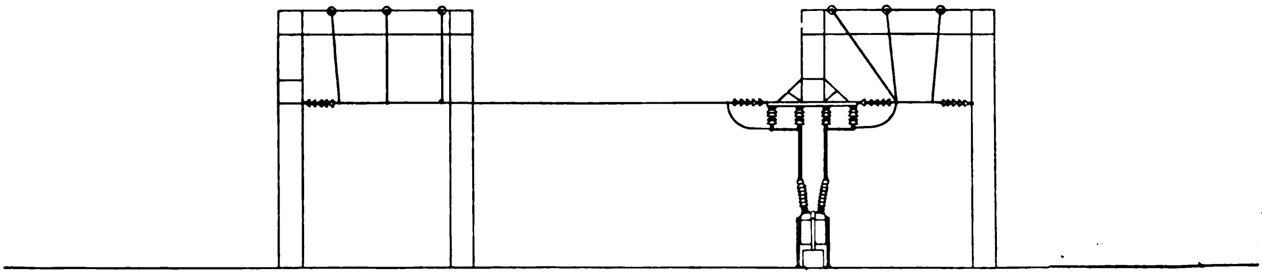
A metal-clad compound-filled switchgear unit is shown in Fig. 26. It should be noted that oil-immersed isolating and busbar selecting switches are employed and the complete three-phase breaker can be withdrawn vertically from the fixed framework by means of an

Clearances for Air-Insulated Conductors.

The minimum space required for super-tension installations depends on the minimum clearances allowable. Recommended values for rigid conductors are given in Fig. 28. Curves A and B indicate clearances to earth for indoor and outdoor gear respectively, whilst clearances between phases are given by curves C and D.

Super-Tension Indoor and Outdoor Installations.

66-kV indoor station.—The busbars and isolators are supported on an open-type steel framework. Expensive



Alternative arrangement of busbar sectionalizing equipment.

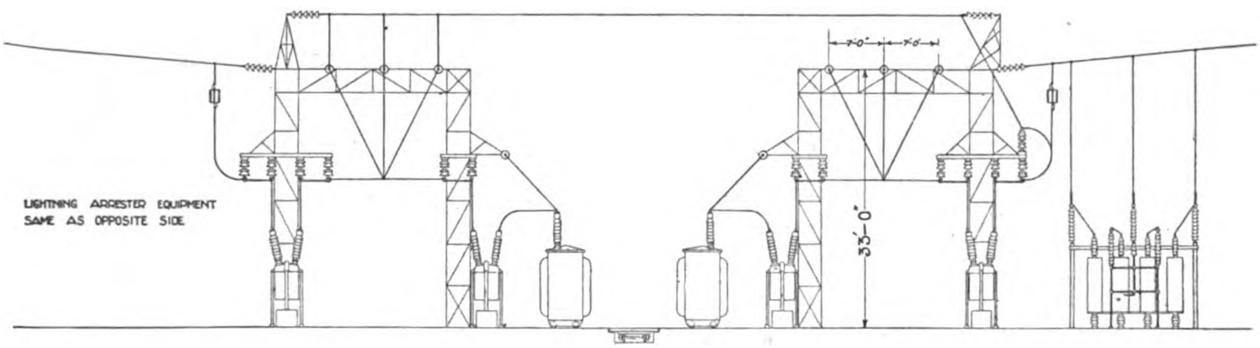


FIG. 32.—Layout of 88-kV outdoor station. Sectional elevation.

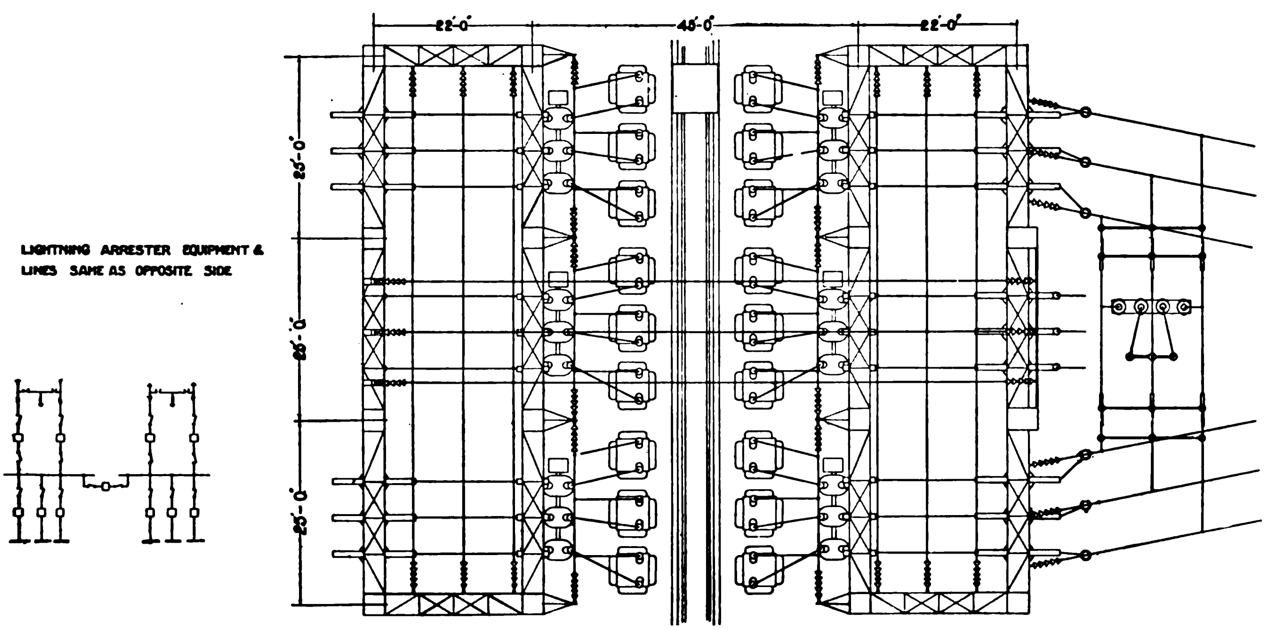


FIG. 33.—Layout of 88-kV outdoor station. Plan.

bushings are avoided, where possible, by the use of large holes in the divisions. All isolating switches are mechanically operated and can be controlled and observed from the ground floor. A sectional elevation and plan are given in Figs. 29 and 30.

88-*kV outdoor station*.—The station is in two halves arranged back to back in order to reduce the length, one set of busbars only being provided, together with a busbar section switch. An alternative arrangement for busbar sectionalizing is shown in the sectional elevation, Fig. 32. A plan of the layout is given in Fig. 33.

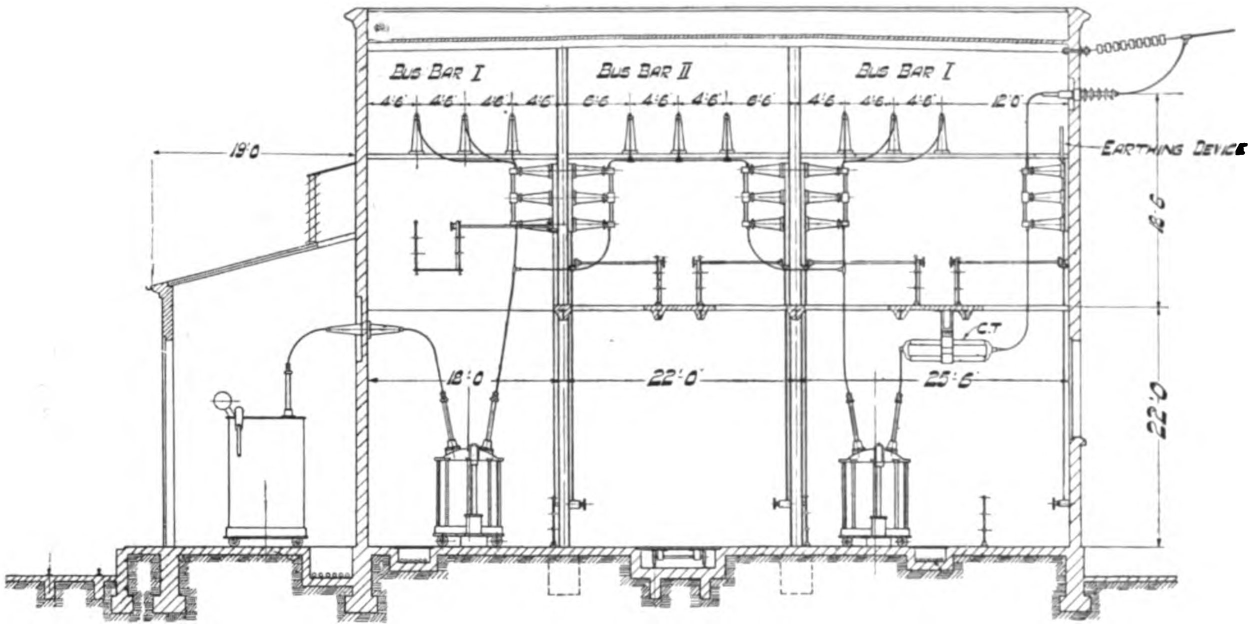


FIG. 34.—Layout of 110-kV indoor station. Sectional elevation.

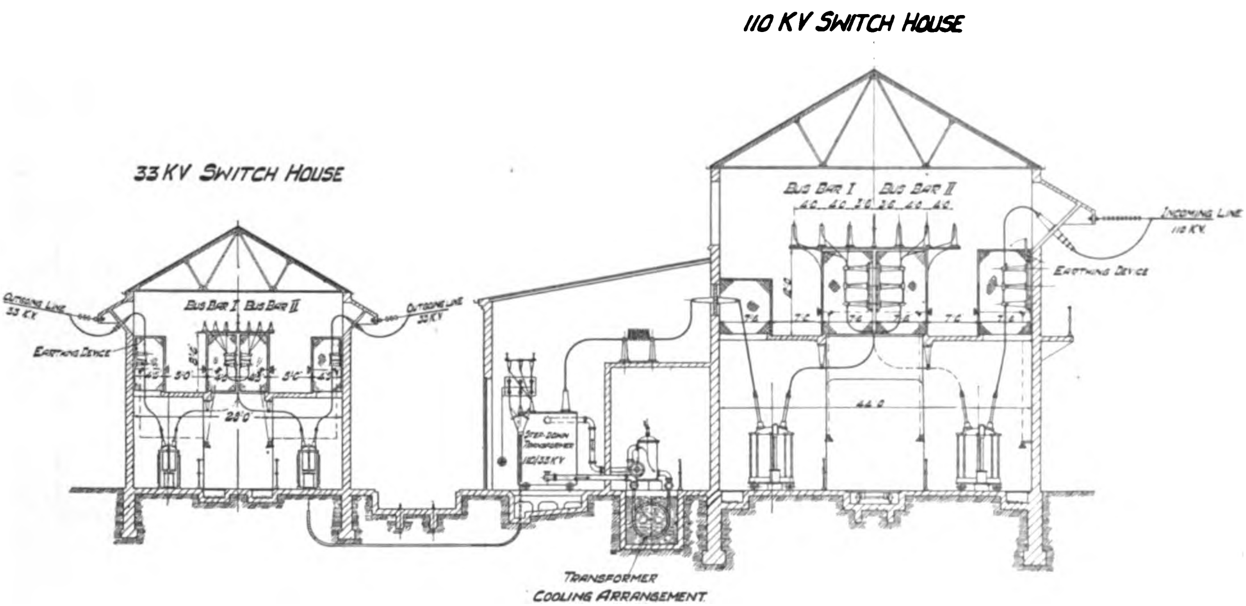


FIG. 35.—Layout of 110/33-kV indoor station. Sectional elevation.

66-*kV outdoor station*.—A sectional elevation of the layout is shown in Fig. 31. Busbar selection is effected by change-over switches. By-pass switches are provided in order that a breaker may be disconnected for repairs without interruption of supply. All insulators are built up from standard units, thus facilitating repairs.

110-*kV indoor station*.—A sectional elevation is shown in Fig. 34. The length of building is reduced by the horseshoe arrangement of one set of busbars. The other set is arranged in a straight run down the centre,

and the breakers are arranged directly opposite to one another in two rows.

110/33-*kV indoor station.*—Separate 110-kV and 33-kV switch rooms are shown in sectional elevation and plan in Figs. 35 and 36 respectively. Duplicate busbars arranged in the usual manner are employed. The breakers are mounted in two rows in zigzag formation. This arrangement makes the breaker cell twice the width of the isolating switch cell, but the extra space may be used for the accommodation of instrument transformers.

A gallery is provided for the inspection of the 110-kV wall-type bushings. All isolating switches can be operated and observed from the ground floor. Both switch rooms are constructed on the same principle.

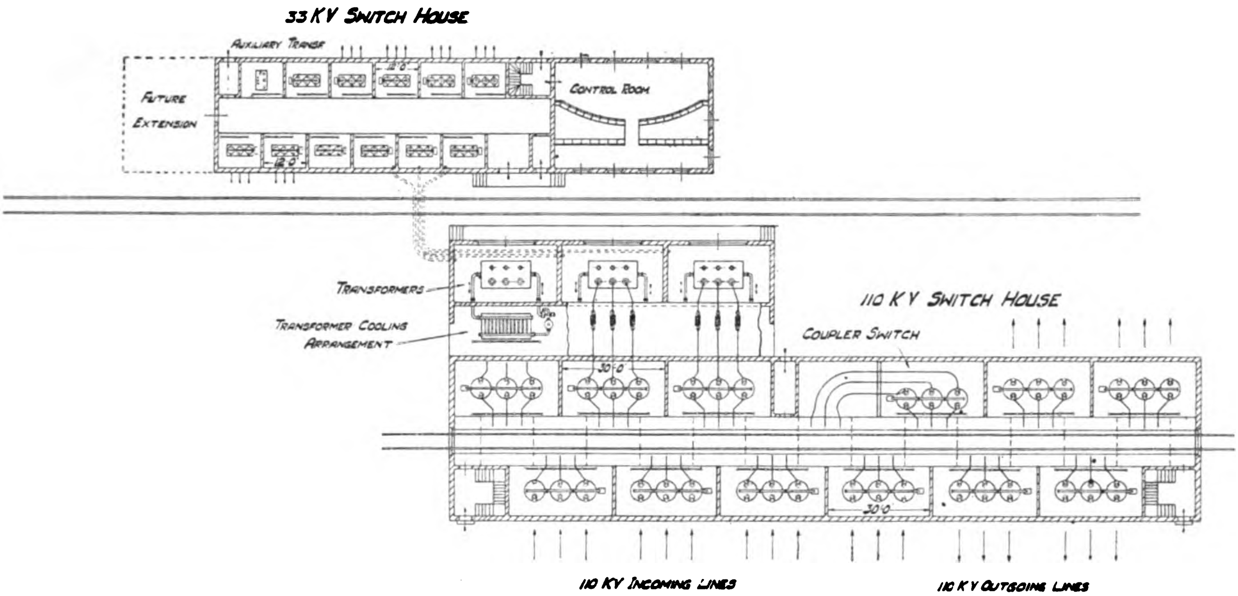


FIG. 36.—Layout of 110/33-kV indoor station. Plan.

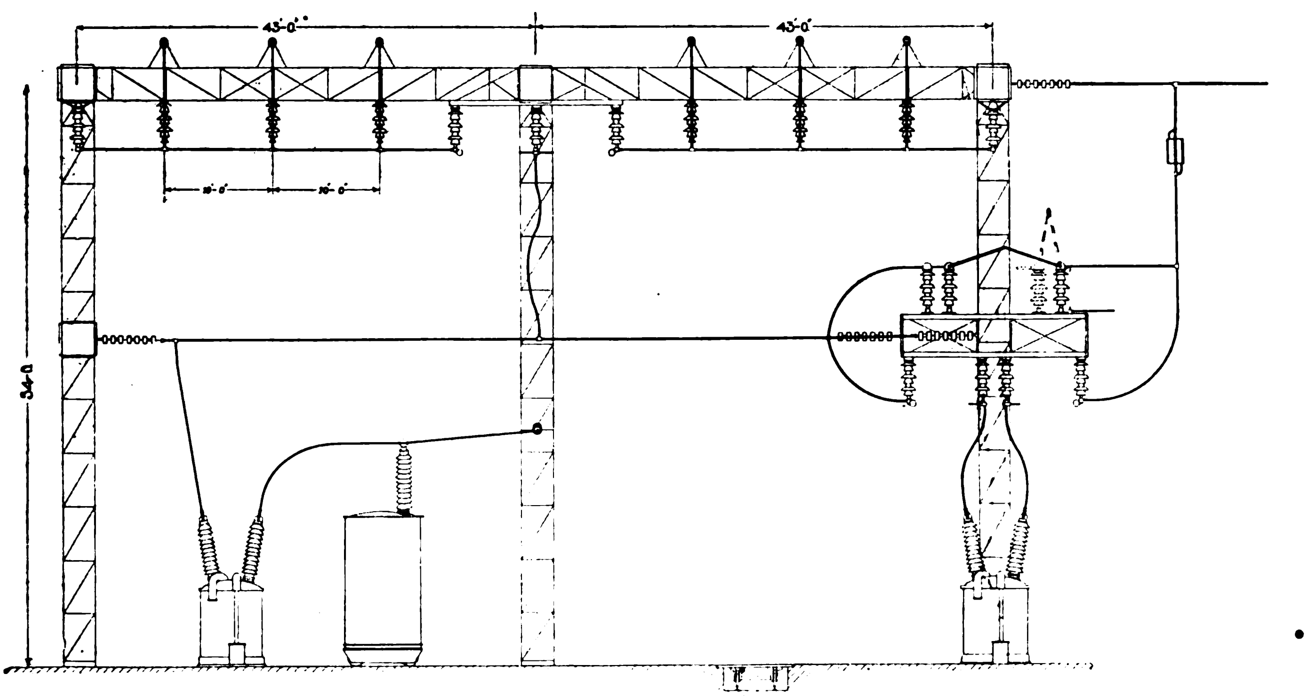


FIG. 37.—Layout of 135-kV outdoor station. Sectional elevation.

135-kV outdoor station.—A duplicate set of strained busbars is employed and selection effected by mechanically-operated, carriage-type change-over switches, as shown in the sectional elevation in Fig. 37. By-pass switches are provided for each line breaker. The layout is shown in plan in Fig. 38.

On the above indoor installations, protection is afforded by expanded-metal screens placed at operating positions on the second floor. All breakers are provided with masonry enclosures for protection while carrying out repairs.

RATINGS.

Oil circuit breakers have two distinct ratings:—

(1) Normal rating.

Voltage.
Current.
Frequency.

(2) Short-circuit rating.

(*a*) Breaking capacity.
(*b*) 5-sec. current capacity.

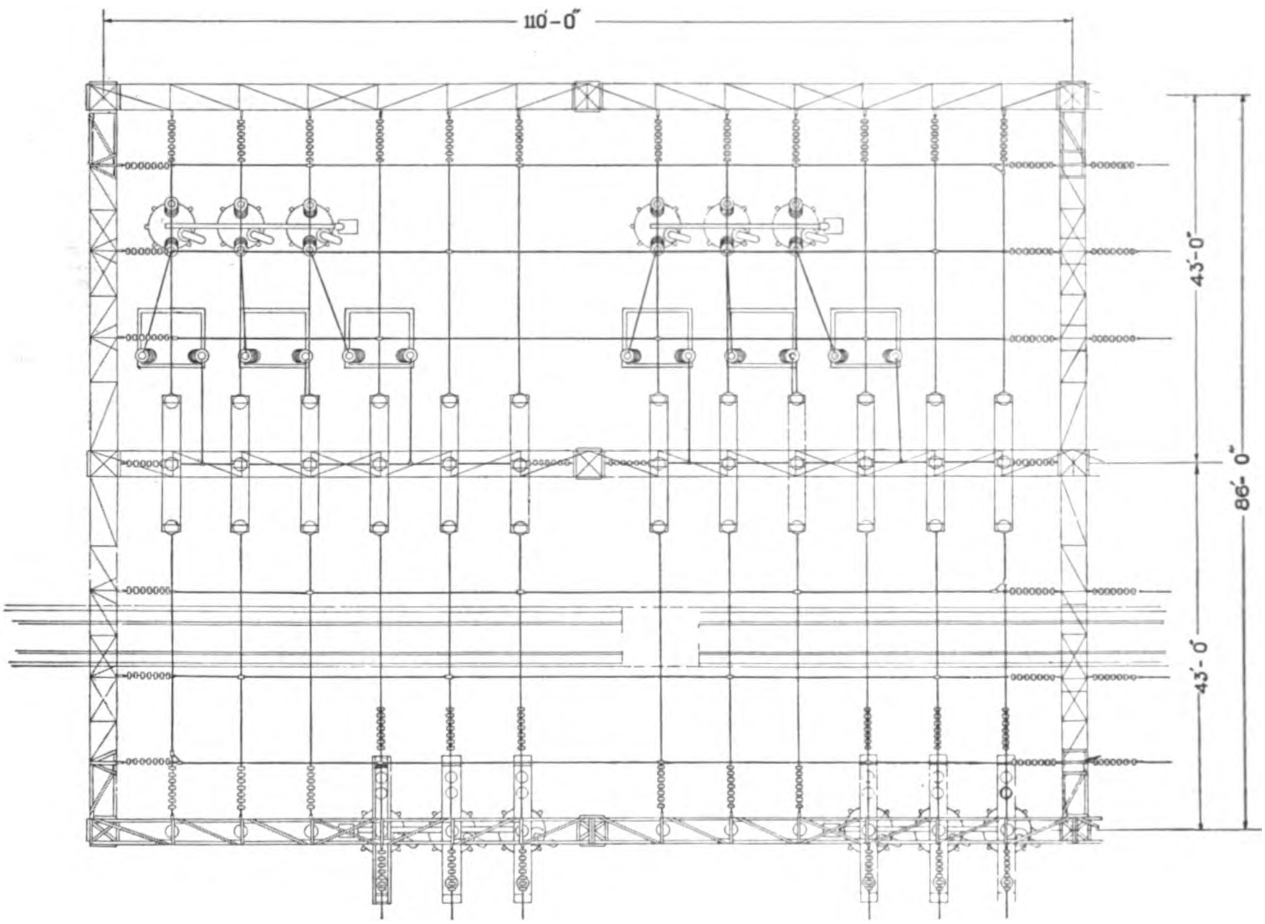


FIG. 38.—Layout of 135-kV outdoor station. Plan.

Section 5.

OIL-IMMERSED CIRCUIT BREAKERS.

Air-break fuses and breakers are satisfactory on small-capacity low-tension a.c. systems, but oil breakers are essential for breaking high-tension a.c. circuits, the principal reason being that an oil breaker breaks the current at or near the zero point of the wave, whereas a fuse or breaker operating in air generally breaks the current at or near the maximum point, thus creating excessive surges.

(1) *Normal rating.*—The British Standard Specification, No. 116, 1923, deals with the breaking capacity and normal rating of oil-immersed circuit breakers. The design of a breaker to fulfil its normal rating presents very little difficulty.

(2) *Short-circuit rating.*

(*a*) *Breaking capacity.*—Research on this subject has been conducted in nearly every country, and the British Electrical and Allied Industries Research Association have urgent need of plant, with a short-circuit capacity up to, say, 750 000 kVA, being placed at their disposal.

Co-operative action in this direction would be of mutual benefit to supply undertakings and manufacturers. Up to the present an increase in the breaking capacity of oil breakers has been obtained very largely by increasing their physical dimensions, whereas it is reasonable to believe that when a scientific basis of design has been evolved the size and cost will be reduced appreciably. Many tests have been carried out in other countries on running systems, without serious interruptions of supply.

The breaking-capacity rating is most important at generating voltages, and is defined as the maximum kVA which the circuit breaker will break on a definite operating duty. The kVA is based on the arc current and the system voltage, presupposing that the normal voltage will be re-established on the opening of the breaker. A better indication of the duty imposed would be obtained by using the recovery voltage instead of the system voltage. The recovery voltage, however, depends on the power factor, the stored energy in the system, the connected shunt load and whether the neutral is earthed or not, and it cannot be easily calculated. The system voltage is therefore taken to represent the average recovery voltage. This point becomes of considerable importance when a relatively small breaker is connected to a large system in such a way that it may afford the only outlet for the stored energy. It is generally conceded that the worst duty imposed on a breaker is operation on a short-circuit at the generator terminals with neutral insulated and no connected shunt load.

Operating duty.—The standard operating duty, both in this country and in America, is for the breaker to interrupt its rated kVA twice at a two-minute interval and then to be in a condition to be closed and carry its rated current until it is practicable to inspect it and make necessary adjustments. This operating duty may not suit the practice of supply undertakings, and in America agreement has been reached as to the percentage of interrupting rating applicable to the following modified duties :—

	Per cent
(1) Two unit-operating cycles separated by a two-minute interval (standard operating duty)	100
(2) Four unit-operating cycles separated by two-minute intervals	70
(3) Four unit-operating cycles separated by half-minute intervals	60
(4) Four unit-operating cycles with no time delay between full open position and start of closing position	30

For the above purpose, each unit-operating cycle consists of closing the breaker on a fault followed immediately by the opening of the breaker, that is, without time-lag. The operating duty therefore begins and ends with the breaker in the open position.

It is evident from the above figures that an attendant can ruin a breaker by closing too frequently on a fault or at too short an interval between unit-operating cycles. The failure of oil breakers after repeatedly opening short-circuits is due, principally, to the ignition of explosive mixtures, which are formed by the combination of the arc gases with the air in the top of the oil vessel. The gases cannot be vented quickly enough to relieve the danger.

Fig. 39 illustrates the operation of a breaker under fault conditions. The short-circuit characteristic for a typical turbo-generator is shown by curve A, which is the B.E.S.A. assumed curve and does not allow for possible doubling effect. Curve B is a breaker-opening characteristic, and both curves are on a common time basis in order to correlate them. It is assumed that the arcing contacts of an average breaker, set for instantaneous tripping, do not separate until 0·2 sec.

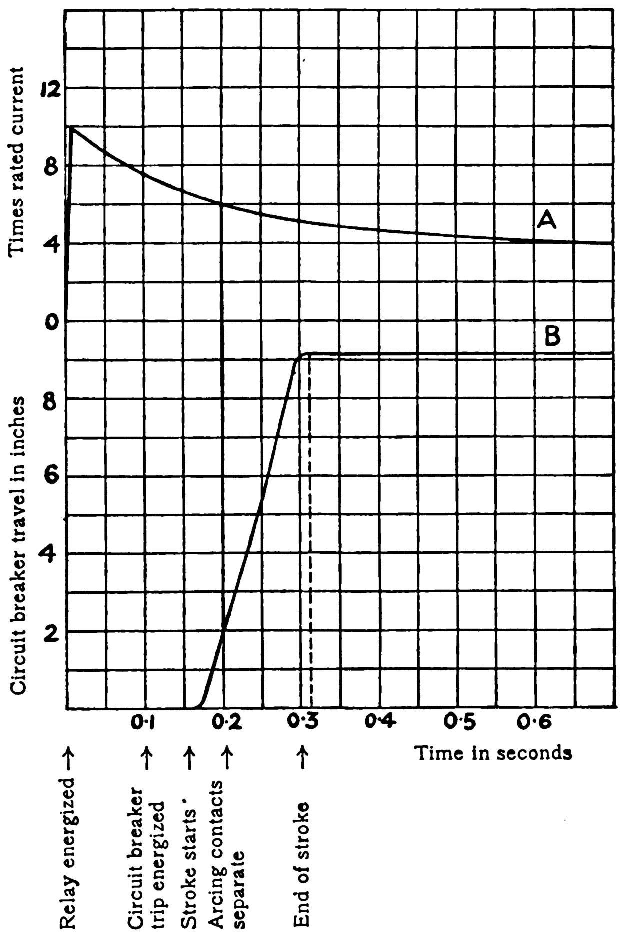


FIG. 39.—Operation of breaker on short-circuit.

has elapsed, and the current to be broken will be that corresponding to six times the aggregate plant capacity. In the case of cable systems a fault may not develop instantaneously, and it is possible for the peak value of the short-circuit to occur at the instant the arcing contacts separate. On this account, important main breakers are often selected with a capacity equal to the peak value of the short-circuit kVA.

Short-circuit rating.

(*b*) *5-sec. current capacity.*—The 5-sec. current capacity is defined as the maximum current that the breaker contacts can pass for five seconds without danger of

welding the contacts or causing mechanical distortion due to electromagnetic forces. This rating should be determined experimentally and is frequently about 50 times the normal current capacity.

Working Principles.

The function of an oil breaker is to break the current in the shortest possible time after the contacts start to separate. The energy of the arc appears as heat, which decomposes a certain amount of oil around the contacts so that a gas stream is formed. At or near each zero value of the current wave the circuit is interrupted and there is an instantaneous voltage-rise, tending to re-establish the arc. This may be termed the recovery voltage and is affected by the conditions of the external circuit, as will be indicated later.

Final interruption of the circuit occurs when the recovery voltage is insufficient to re-establish the arc, and in order to accomplish this in the shortest possible time the opening speed of the breaker must be sufficiently high. Operation at the normal rating presents no difficulty. It is the short-circuit rating which demands the greater attention, and which at generating voltages determines the size and cost.

Factors Affecting Breaking Capacity.

The fundamental laws governing the breaking of heavy power arcs under oil have not yet been discovered, and when a systematic investigation of an oil breaker is attempted its erratic behaviour under short-circuit conditions soon becomes evident. The severity of a short-circuit depends upon the point of the voltage wave at which it occurs, and even if a large number of tests be carried out under constant and controlled conditions the amount of gas generated may vary several hundred per cent. Since the final measure of the efficiency of a given breaker is the amount of gas generated and the rate of generation, it follows that a single test is inconclusive, and the only safe breaking capacity that can be ascribed to the breaker is that obtained from many tests made at all capacities under the worst conditions.

The factors which influence the breaking capacity of an oil breaker are :—

(1) Opening speed; that is, speed at instant of contact separation.
(2) Number of breaks per phase.
(3) Length of break.
(4) Head of oil above point of break.
(5) Volume of air cushion.
(6) Type and size of vents.
(7) Shape and strength of top plate, oil tank and fastenings.
(8) Clearances in air and under oil.
(9) Characteristics of the oil.
(10) Volume of oil.

(1) *Opening speed*.—The initial acceleration of a breaker should be high in order to get sufficient speed at the instant the arcing contacts separate. It is the speed at this point that is of most importance. A high opening speed is usually obtained by means of accelerating springs and a reduction of the weight of the moving parts to a minimum. In the case of heavy-current breakers, where the acceleration of heavy moving parts becomes difficult, the necessary speed at the instant of contact separation is usually obtained by means of spring-operated arcing contacts or by the use of an external snap switch, in which the arc is ruptured.

Ideal conditions require that the arc shall not re-establish itself after passing the first zero value of current following the separation of the arcing contacts, and this emphasizes the value of a high opening speed. A slow breaker may allow the current to persist for several half-cycles after the contacts have separated, and would thus have to dissipate much more energy.

From tests carried out at generating voltages by various observers it appears that no advantage is gained by an increase in the opening speed beyond a certain figure. Various values ranging between 3·5 and 7 ft. per sec. have been given. Tests have shown that opening speeds in excess of the best value result in a longer arc, increased gas generation and increased internal pressures, except in the case of the explosion-pot breaker.

The speed of a breaker when breaking heavy short-circuit currents at generating voltages tends to exceed its no-load speed due to the electromagnetic throw-off force exerted on the moving contact bar, as illustrated in Fig. 41.

In cases where the contact-bar lifting-rods pass through the top plate, the internal pressure developed may exert sufficient force on the former to reduce the opening speed. In such designs it is essential to reduce the diameter of the rods to a minimum.

(2) *Number of breaks per phase*.—In the majority of cases oil breakers are designed with two breaks per phase, but on the Continent as many as ten breaks per phase are occasionally used. The advantages of the increased number of breaks are not so great as were anticipated, and tests carried out on the Continent gave the following results for an increase from four to fourteen breaks per phase. The duration of the arc was reduced by about 50 per cent, whilst the aggregate length of the different portions of the arc was increased by 25 per cent. The impulse pressures were more pronounced by about 50 per cent, and the arc energy was only reduced by about 23 per cent. On Continental breakers, which are handwheel-operated, the use of multiple breaks enables a suitable length of break to be obtained on high-voltage gear, but where the mode of operation permits of a longer travel it is doubtful whether the small advantage due to multiple breaks warrants the necessary complication.

The above conclusion may have to be modified in view of a recent patent taken out by the British Electrical and Allied Industries Research Association in connection with multiple breaks. The outstanding feature of the invention is that the breaks are not simultaneous in operation, but are so arranged that they open successively during a cycle or a part thereof. It is claimed that the arc energy is substantially reduced by the timing of the breaks, because at least one pair of contacts will open near the zero value of the wave.

(3) *Length of break*.—The length of break must be

ample in order that the arc may be interrupted, under the worst conditions, without permanent gas generation, otherwise the breaker will quickly be destroyed. At one time it was thought that the breaking capacity was a direct function of the length of break. This assumption has been disproved and it is now known that the main factor which determines the minimum length of break is the rated voltage. Tests carried out at generating voltages have shown that well-designed breakers can break the arc at the end of one-half cycle after the arcing contacts separate. Assuming the above figure for the period of arc duration, then with an opening speed of 5 ft. per sec. the length of arc per break would be 1·2 in. at 25 cycles, and 0·6 in. at 50 cycles. Very big factors of safety have, however, to be allowed, because the throw-off force on the moving contact bar may increase the speed materially and thus lengthen the arc. Furthermore, the recovery voltage has an effect on the minimum length of break that can be employed. The author has never met a case where a breaker has failed due to the length of break being insufficient.

(4) *Head of oil above point of break.*—If the head of oil be insufficient, the amount of gas generated may cause a continuous stream of gas from the contacts to the oil surface. This has been termed "chimney" effect, and under these conditions it is almost certain that an explosive mixture will be formed and fired by the arc, with possible fracture of the top plate. For generating voltages the minimum head of oil that can be used is that necessary to avoid "chimney" effect, whereas on higher voltages the creepage distance over the terminal bushing becomes the deciding factor. Oil throw, gas ignition, and the impulse pressures developed above and below oil level are influenced by the head of oil. A good head of oil gives increased cooling to the rising gases, but tests have shown that too much oil in the tank is as bad as too little. The most suitable head of oil depends on the form of the breaker and must be considered in conjunction with the volume of air cushion.

(5) *Volume of air cushion.*—The volume of air cushion affects the tank pressures, oil throw, arc stabilizing, secondary explosions and gas ignition. The diffusion of the arc gases into the air cushion may form an explosive mixture which may be fired by compression or by a hot bubble of gas on a second fault, for by this time the mixture will be well diffused and easily fired. The volume of the air cushion required will depend on the size and efficiency of the breaker. An air cushion having a volume equal to about one-third that of the tank gives satisfactory results.

(6) *Type and size of vents.*—The problem of breaking heavy power arcs under oil presents the most difficulty at generating voltages, and in order to get the maximum breaking capacity in a given space it is necessary to provide means for freely venting large amounts of gases without oil-throwing. With short vent pipes, baffles are needed to prevent the ejection of oil, but it is essential to avoid over-baffling, or otherwise free venting will not be effected. The greatest risk of explosion occurs on repeated operations, because in this case the gases generated on the first opening have time to diffuse into the air cushion and so produce a mixture, which is readily ignited and through which flame can travel with explosive violence. A vent pipe does not relieve the maximum instantaneous internal pressure. It is desirable to keep the vent pipes for each breaker separate from the rest, and to carry them well away from the breaker terminals, preferably to the exterior of the building, to avoid breakdown between the terminals, due to the presence of hot, ionized gases. If a common exhaust pipe be used there is a danger of explosion in the piping due to trapped gases being fired from an explosion in a breaker.

(7) *Shape and strength of top plate, oil tank and fastenings.*—The explosive pressures produced in a breaker may be considered under three separate headings :—

(*a*) The impulse pressures due to the sudden generation of a comparatively large volume of gas in a confined space.
(*b*) The pressure developed in the air cushion due to the increase in volume and temperature of the resulting mixture of air and arc gases.
(*c*) The pressure generated by possible ignition of the explosive mixture present above the oil surface.

The maximum pressure developed will depend probably upon the extent to which the tank gives, and the pressure exerted. A rectangular tank gives at the sides more readily than a circular one, and the energy is thus absorbed without excessive pressure developing. On the other hand, circular tanks are built to withstand the high pressures without distortion, and either shape of tank may be used providing it has sufficient strength.

Actual tests on heavy breakers have recorded tank pressures of 200 to 300 lb. per square inch.

(8) *Clearances in air and under oil.*—The safe clearances depend on the voltage, circuit conditions, and amount of current interrupted, and no earthed metal should be below oil level in any position where bubbles of gas may be expected. Tank linings and phase barriers are occasionally omitted on Continental breakers, and greater clearances to earth and between phases are necessary. Minimum air clearances and test pressures are specified in British Standard Specification No. 116, 1923.

(9) *Characteristics of the oil.*—The breaking capacity of an oil breaker is influenced by the characteristics of the oil more than is generally understood. The most suitable oil is one which :—

(*a*) Produces the least quantity of gas for a given interruption.
(*b*) Has the least carbon production.
(*c*) Has the most suitable viscosity.
(*d*) Has the highest electric strength for a given interruption.
(*e*) Vaporizes the least.
(*f*) Has the greatest percentage carbon precipitation.
(*g*) Absorbs the least quantity of moisture.
(*h*) Has the highest flash point.

Standard transformer oil is frequently used at ordinary operating temperatures, but where breakers have to work in cold climates an oil which remains fluid must

be used. Alternatively, immersion heaters may be employed.

(10) *Volume of oil.*—Strictly speaking, this factor cannot be separated from head of oil. A sufficient quantity must be provided to ensure ample cooling of the arc and the gases generated. Fig. 40 gives a set of curves (B), (A) and (C), showing the relation between rated breaking capacity and volume of oil for typical British, American and Continental breakers respectively.

Continental breakers have larger clearances, giving a greater volume of oil, but the tanks are weaker than those of British and American design.

From the attempt to segregate the main factors which influence the breaking capacity of an oil circuit breaker, it will be evident that all the variables are

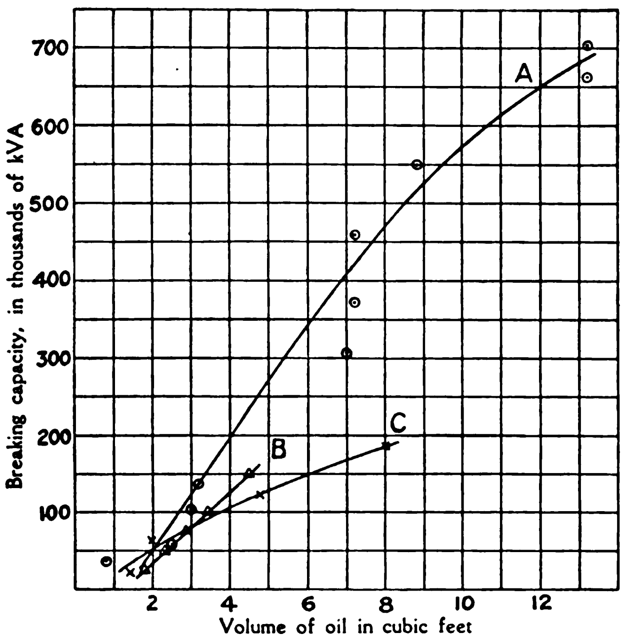


FIG. 40.—Relation of breaking capacity to volume of oil.

interdependent and some of them cannot be controlled by the designer.

CONDITIONS OF THE EXTERNAL CIRCUIT.

The duty imposed on a breaker is affected by the conditions of the external circuit as regards the following characteristics :—

(*a*) Earthed or unearthed system.
(*b*) Power factor under short-circuit conditions.
(*c*) Periodicity.
(*d*) Connected shunt load.

The recovery voltage which is produced at every circuit interruption is affected by the above four factors. It is considerably greater on unearthed systems and short-circuits of low power factor. Connected shunt load reduces the recovery voltage, and hence for a given periodicity of supply the worst circuit conditions are when the fault occurs at the generator terminals on an unearthed system without connected shunt load.

Tests have shown that the breaking capacity of a given breaker on a 60-cycle system is greater than that on a 25-cycle system. At the former frequency the arc energy per half-cycle is only two-fifths that on the latter frequency, and the opportunity for breaking the current occurs more frequently.

THERMAL AND ELECTROMAGNETIC EFFECTS.

The effects produced by short-circuit current are :—

(1) Electromagnetic stresses.
(2) Rapid heating of conductors.

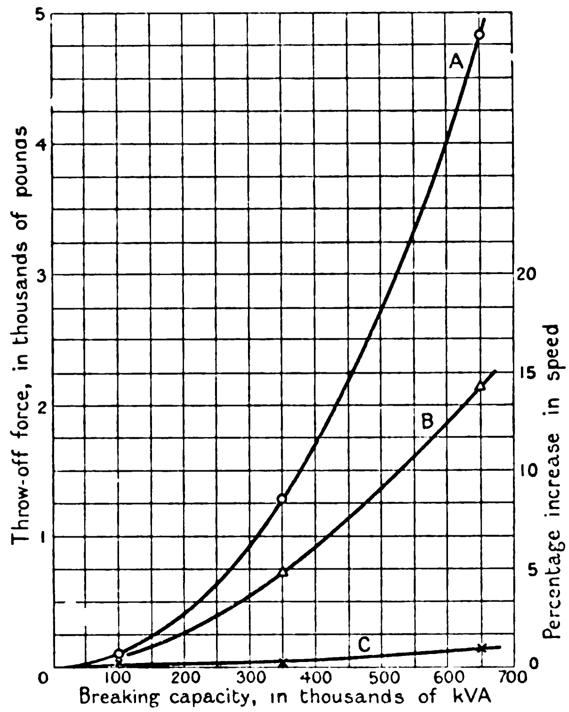


FIG. 41.—Relation of throw-off force and speed increment to breaking capacity.

ELECTROMAGNETIC STRESSES.

There are two forces to be considered :—

(*a*) Throw-off force on the moving contact bar.
(*b*) Repulsive force on the breaker terminals.

(*a*) *Throw-off force.*—The moving contact bar and the breaker terminals form a loop, and in consequence short-circuit currents produce a throw-off force on the former. Fig. 41 gives curves showing the calculated throw-off forces and their effects on the opening speeds of breakers of various breaking capacities. Curve A gives the highest peak value of throw-off force per phase before the arcing contacts separate. The values shown on curve C are the mean values of throw-off force per phase during the first half-cycle of the arc. The percentage increase in opening speed is given by curve B. The curves are based on a line of breakers rated up to 650 000 kVA, and all figures are calculated for the full rating of each breaker.

The breaker mechanism must be strong enough to resist the throw-off force without excessive deflection

of the various mechanical parts, otherwise the main contacts will separate at each instant when the current attains its peak value. In such a case, arcing would occur at the main contacts, with possible welding, before the trip coil released the breaker.

(*b*) ***Repulsive force on breaker terminals.***—The terminal studs experience a mutual repulsive force due to the flow of short-circuit current along parallel conductors in opposite directions. Each stud may be considered to be a uniformly-loaded cantilever, and the fixed contact blocks will be deflected due to the loading caused by the short-circuit currents. Where porcelain insulators are used they will relieve the stud of the repulsive load up to the breaking limit of the former, but where bakelized paper insulation is employed it will accommodate itself up to the elastic limit of the copper.

The curves shown in Fig. 42 give the calculated repulsive forces and consequent deflection of the contact

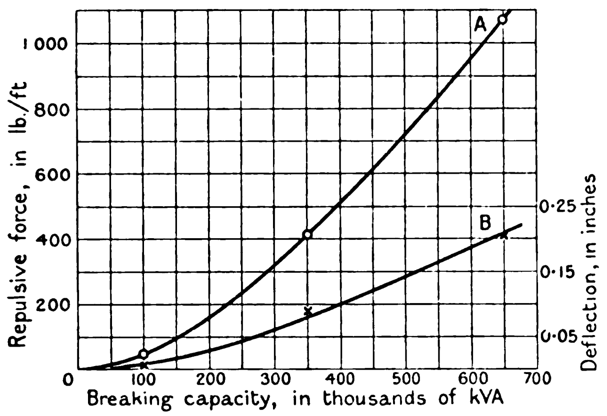


FIG. 42.—Repulsive force and deflection in relation to breaking capacity.

blocks at the ends of the terminals, on the assumption that the insulators do not offer any resistance. Figures are given for breaking capacity ratings up to 650 000 kVA. Curve A gives the highest peak value of repulsive force in lb. per foot run of the terminal before the breaker opens, whilst curve B gives the deflection of the contact blocks in inches.

Repulsive and throw-off forces should be calculated for a current equal to five times the rated arc amperes, in order to allow for possible doubling effect, and Figs. 41 and 42 are based on this value. In view of the serious forces which may be experienced at the instant of closing a breaker on an existing fault, it is necessary that a quick-closing action be obtained in order to relieve the auxiliary contacts as soon as possible and get the breaker home against the heavy forces, as otherwise a reduced opening speed will be the consequence.

RAPID HEATING OF CONDUCTORS.

On large plants it is necessary to limit the minimum section of conductor allowable near to the source of power on account of high current densities which may be obtained at the moment of short-circuit. At a density of 100 000 amperes per square inch, the initial rate of temperature-rise would be 120 deg. C. per second. Fig. 43 illustrates the rapid heating of the terminals of a typical breaker rated at 650 000 kVA. Curve A is an unsymmetrical short-circuit characteristic for a generator having 10 per cent inherent reactance. Curve B gives the temperature-rise of the breaker terminals where tripping does not occur until 5 seconds have elapsed. The equivalent steady current, which would produce the same temperature-rise at the end of 5 seconds, is shown in curve C. The curves are calculated for a short-circuit current such that with tripping at the end of 0·2 sec. the breaker would be rupturing its rated kVA.

The preheating of arcing contacts is minimized by liberal design, and in many cases there is more copper

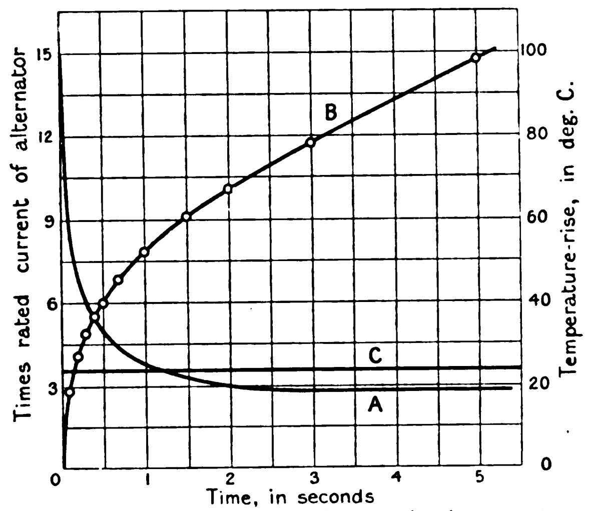


FIG. 43.—Thermal effect of short-circuit current.

necessary in the arcing contacts than in the main contacts.

CONSTRUCTIONAL FEATURES.

The modern oil breaker is characterized by its strength of tank and top plate, absence of external mechanism, improved venting, and substantial main and arcing contacts.

TERMINAL BUSHINGS.

For breakers up to 33 kV, plain insulators of porcelain or bakelized paper are satisfactory. For higher voltages a composite construction becomes necessary, and two types have been evolved, namely, the condenser type and the oil or compound-filled type. At 110 kV the cost of the terminal bushings may easily be 50 per cent of the total cost of the breaker.

MAIN CONTACTS.

The following forms of main contacts are to be found on modern breakers :—

(*a*) Wedge type.
(*b*) Laminated brush.
(*c*) Wound brush.
(*d*) Reverse brush.
(*e*) Butt type.

(*a*) *Wedge contacts.*—The fixed contacts consist of pairs of fingers between which moves the wedge-shaped moving contact bar. They are easily adjusted and are self-aligning. The variation of contact pressure is very small for a wide range of wedge position. The pressure used is of the order of 8 lb. per square inch, with a contact current density of 100–150 amperes per square inch.

Several pairs of fingers are used for heavy currents, and on short-circuit the current divides equally between the contacts of each pair, consequently the fingers are attracted to each other, giving an increased contact pressure. This form of contact is eminently suitable for heavy duty, because each finger is reinforced with a steel backing spring, and a constant pressure is maintained. A first-class wiping action is obtained, and the contact surface is divided into a number of unit areas, each of which can be readily renewed without affecting the rest. Further, a greater deflection of the mechanism is permissible under the action of the initial short-circuit current without fear of welding of the contacts before the trip coil has released the breaker.

(*b*) *Laminated brush.*—The fixed contacts consist of plain copper blocks on the under surface of which a laminated brush makes contact. A finer setting and more accurate workmanship is required than for the wedge type, and the conductivity is seriously affected by a very small variation in the relative position of contact block and brush holder. This type is generally worked at a current density of 250 amperes per square inch, with a pressure of 15–50 lb. per square inch. The elasticity of the brush deteriorates with time and proves faulty under the action of the throw-off force set up on short-circuit.

(*c*) *Wound brush.*—This is an improved form of laminated brush of broad **U** shape, with the ends or the laminations bedding almost normal to the under face of the fixed contacts. Flexure in the brush is taken at the back of the **U**, and, consequently, variations in the relative position of the brush holder and contact block do not affect the contacts of individual laminations to the same extent as the ordinary form. With the wound brush, a current density of 500 amperes per square inch can be used at a pressure of 100 lb., or more, per square inch. Under the action of the throw-off force this brush may prove faulty.

(*d*) *Reverse brush.*—This type of contact is an improvement on the wound brush in so much that any deflection of the brush under the action of the throw-off force tends to increase the contact pressure. A laminated brush is fitted on each terminal and each is similar to half of a wound brush but is mounted the reverse way so that the ends of the laminations bed almost normally to the upper face of a straight moving contact bar. This construction increases the number of joints per phase.

(*e*) *Butt type.*—This form of contact is only practicable for handling small currents, on account of the low current density permissible.

ARCING CONTACTS.

In order that the current may be transferred cleanly from the main to the arcing contacts, it is necessary that the contact resistance of the latter should be reduced to a minimum. The arcing contacts should not separate until the main contacts are well clear. The life of a breaker between the periods of inspection and repair is principally a function of the amount of copper in the arcing contacts, and they should be given the maximum amount of care as regards cleaning and replacements if the breaking capacity is to be maintained at its rated value. The most common forms of arcing contacts are :—

(*a*) Controller finger type.
(*b*) Flat finger type.
(*c*) Butt type.
(*d*) Latched plug type.

(*a*) *Controller finger contact.*—This takes the form of a semi-cylindrical block of copper carried on a flat spring riveted to the under side of the moving contact bar. The block makes a line contact with a flat plate carried by the fixed contact block. The semi-cylindrical block has a slight rolling action as the breaker opens, thus shifting the position of the contact. This form is only suitable for light duty.

(*b*) *Flat finger contact.*—This type is similar to the wedge main contact except that the two main faces of the wedge are parallel and vertical. The fingers are fitted with very strong backing springs and have only a limited play in a horizontal direction to avoid damage in case of a bad entrance of the moving arcing contact, which consists of a heavy block of copper having parallel vertical sides. The top of this block has a blunted **V** shape to give good entrance between the fingers and to take the arcing. It is necessary to have a sufficiently high opening speed with this type of contact, due to the danger of welding as the moving contact slides off the fingers.

(*c*) *Butt contact.*—This form consists of two cylinders of copper, their flat faces butting together. One contact is held to the other by means of a spring so that they do not separate until the main contacts are well clear. The spring contact may be fitted on either the fixed or movable element of the breaker. The current density is not decreased before separation of the contacts as is the case with the flat finger type.

(*d*) *Latched plug contact.*—The contact is obtained by a plug and socket, the plug definitely latching with the socket. The former is carried on a spring-loaded telescope attached to the fixed main contact block, and both arcing contacts are carried down together until the telescope is extended. When the springs are almost fully compressed, a fixed stop arrests the travel of the plug and the contacts are disengaged, separating at a high speed due to the combined effect of the opening of the breaker and the action of the compressed spring. This form of contact is generally applied to super-tension breakers having a considerable length of break, and it is essential to avoid corners or edges on the contacts to eliminate brush discharges. Generally all contacts are enclosed in electrostatic shields having rounded contours.

At high current ratings, where it is difficult to accelerate the heavy moving parts, a separate spring-operated snap breaker is frequently used for final

rupture of the current and is connected in parallel with the main breaker. The snap breaker is timed to close before, and open after, the main contacts.

OPERATING MECHANISM.

It is essential that the operating mechanism should be robust, especially on heavy-duty breakers, in order

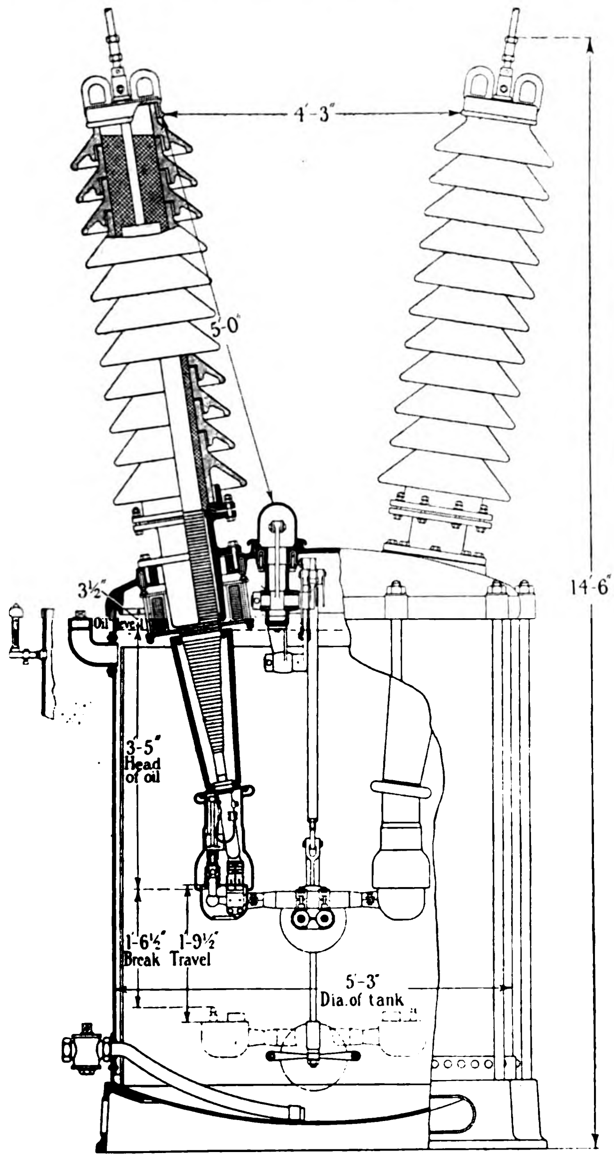


FIG. 44.—135-kV outdoor oil circuit breaker.

to resist the instantaneous short-circuit stresses and the repeated shocks of normal operation. An internal mechanism is preferable because it eliminates the reclosing tendency due to internal pressures which are developed on short-circuit. Furthermore, there is no earthed metal between the terminals and no chance of gases leaking through the top plate, except along the legitimate path offered by the vent pipes.

It should be possible for a breaker to trip free of the handle, under the action of the release coils at any stage of the closing movement. If the trip gear only functions when the breaker is fully home there is always the possibility of it being held in partial contact and thereby causing considerable damage. The operating and tripping mechanism should be preferably at the front of the breaker in an accessible position, as is the case with British and American designs.

BREAKER STRUCTURE.

The complete structure, consisting of top plate, oil tank, vents and fastenings, should be a good mechanical job. On heavy-duty breakers the structure is built on the lines of steam boiler practice, i.e. cylindrical boiler-plate tanks with belled ends, held to the top plate by means of a steel cradle and tie rods. Up to 88 kV, breakers are frame-mounted, allowing the internal portion to be inspected by lowering the tanks. On higher voltages, breakers are supported directly on the floor by means of the cradle. Access to the interior, after emptying the tank, is gained by means of a manhole.

Oil tanks should be fitted with an insulating lining capable of withstanding the full test voltage. In the ordinary breaker the arc is magnetically attracted to the side of the tank. The lining safeguards the breaker in this respect and allows smaller clearances to be used than would otherwise be the case. Most manufacturers leave a layer of oil between the lining and the tank side.

For outdoor service the breaker terminals are shrouded in porcelain petticoats, and the structure is made weatherproof. A typical 135-kV outdoor breaker is illustrated in Fig. 44.

RESISTANCE CIRCUIT BREAKERS.

On the Continent, resistances are commonly used in conjunction with oil breakers, either to minimize shocks to the system due to switching operations or to relieve the duty on the breaker. Resistances may be fitted for the following duties :—

(1) To limit the transient currents when switching-in transformers and high-tension motors.
(2) To limit the voltage surge when switching-out a transformer.
(3) To limit the voltage surge when switching long transmission lines.
(4) To limit the duty on oil breakers when opening short-circuits.

Breakers fitted with resistances open or close in two stages, and in the case of resistance breakers for transformers, motors, or transmission lines, a set of auxiliary contacts is provided so that the resistance is first inserted, thus reducing the current rush, and finally it is short-circuited when the main contacts are bridged. Very often the resistances are fitted either to the under side of the moving contact bar or at the bottom of the guide rods, this latter case necessitating a flexible connection. In cases where the resistance is external, a third terminal is required on the breaker. This is generally embodied in a split-conductor terminal, each of the two conductors being lightly insulated from each other. One stem carries the main contacts, whilst the

other is fitted with a leading contact, and the resistance is connected between the stems.

The principle of using a resistance for reduction of the duty imposed on a breaker is an excellent one. The resistance absorbs real energy but becomes heated in the case of delayed operation and may be destroyed. The necessary contacts and insulation for such a resistance and also the question of mechanical forces, form a serious problem, and it is doubtful whether the complications are warranted.

Explosion-Pot Circuit Breakers.

The construction of this type only differs from the plain breaker in that the arcing and main contacts are enclosed in strong steel explosion pots. The latter are of drawn steel and are capable of resisting the impulse pressures or any internal pressures developed due to ignition. Some forms of the explosion-pot breaker have the main contacts in air. Each of the two breaks per phase is effected by the withdrawal of a long plug from a socket in each pot. The two plugs are carried upright on the moving crossbar, which is operated by the breaker mechanism. The small space prevents free expansion of the gases, which are developed when the arc is drawn inside the explosion pot, consequently high internal pressures are obtained and, until the pressure is relieved through the throat of the explosion pot, the arc resistance has a high value. As soon as the plug has left the throat, the hot gases are projected downwards into cold oil and the arc is extinguished. The pressure of the gas generated automatically increases the opening speed as the amount of short-circuit energy increases. The most dangerous explosions are due to secondary gas explosions in the air cushion and not excessive arc energy, and it would be unwise to use a weak tank in conjunction with explosion pots on breakers operating at generating voltages. If the oil tank has sufficient strength to withstand the explosions, then it appears that explosion pots are unnecessary.

The author wishes to acknowledge the help rendered by his assistants, Mr. F. Clegg, Mr. V. A. Brown and Mr. B. Burt, in the preparation of this paper; and also his indebtedness to Messrs. Ferguson, Pailin, Ltd., for all the illustrations, except Figs. 7 and 26, the first of which is reproduced by kind permission of Messrs. British Thomson-Houston Co., Ltd., and the second by Messrs. A. Reyrolle and Co., Ltd.

WIRELESS SECTION: CHAIRMAN'S ADDRESS

By Major B. Binyon, O.B.E., M.A., Member.

(*Address delivered 4th November*, 1925.)

I should like to take this opportunity of expressing my thanks and appreciation for the honour you have done me in electing me Chairman of the Wireless Section.

Since the formation of the Section in 1920, the untiring efforts of your past Chairmen, Prof. Eccles, Prof. Howe and Mr. Shaughnessy, backed by strong and representative Committees, have maintained for the Wireless Section a high standard, and I am duly sensible of the responsibility that now falls upon me at a time which I think is somewhat critical in the further development of this important Section of the Institution.

Prof. Eccles, in his Inaugural Address * as Chairman in November 1920, made reference to a movement which had been started for the formation of a society of professional radio engineers analogous to the Institute of Radio Engineers of America, and many of you will have seen from recent correspondence in the technical Press that this subject has again come to the fore.

The intensive development of wireless during the war necessitated interchange of information and experience gained by radio engineers through the medium of an organized society, and the foresight of the late Mr. C. H. Wordingham, C.B.E., then President of the Institution, and Prof. Eccles, led to the formation of the Wireless Section.

With the advent of broadcasting, the field of radio engineering has again been widely extended and a large manufacturing business developed. With the popular interest which this subject has aroused it is not unnatural that the demand for an independent Institution of Radio Engineers should again arise. I wish to assure you that this matter is receiving the most earnest attention of your Committee, who are making a number of recommendations for submission to the Council of the Institution.

We recognize that the Wireless Section is primarily for professional men engaged in radio engineering—the amateur is already well catered for by other organizations—and it is not to our interests to seek any enlargement of membership at the expense of status. Moreover, it is our duty to uphold the status of the Institution, if only in recognition of the debt of gratitude we owe them for our formation. We must, however, not forget that a large number of new workers have been drafted into the radio field, and that some of the best wireless work has been contributed by physicists and other scientists whose training and vocation is not that of an electrical engineer.

Any narrowness in our outlook will invariably foster the formation of organizations to deal with specialized branches of radio work, and I must confess that I have noticed among the radio engineers of pre-broadcasting days a tendency to regard with some contempt those now engaged upon the design of broadcast receiving apparatus, and it is perhaps significant that with one or two exceptions this subject has hitherto been very largely ignored in papers read before this Section.

Anyone who made a careful survey of the recent wireless exhibitions cannot fail to have been impressed by two things: (1) The magnitude of the industry which the advent of broadcasting has created; (2) the great variety in design of the exhibits. Variety in design is inevitable, and perhaps desirable, in any new industry, and in many cases displays considerable ingenuity, ingenuity which I fear is sometimes directed to secure a sales point rather than a scientific advance, but I think we are now approaching a stage when really scientific methods involving accurate measurement and quantitative investigations will be applied to the design of broadcast receiving apparatus. For example, whilst the human ear may be the public's guide in the choice of a loud-speaker, it is far too unreliable a testing instrument for those engaged on loud-speaker investigations. It is to be hoped, therefore, that the older generation of radio engineers will recognize that this new and growing industry well merits their close attention.

I believe it has become a recognized custom for a Chairman in his Address to present a summary or digest of progress in a general manner rather than to deal with one specific technical aspect, but in reviewing the papers which have been read before the Section I find two phases of the wireless art which have been but scantily dealt with—the first I have already mentioned, namely, the design of broadcasting receiving apparatus, the second is the progress which has been made in marine wireless equipments, papers on which, with one exception, have confined themselves largely to direction-finding at sea.

Marine wireless has come to be regarded in the popular imagination as the most backward section of the art. To the broadcast listener it is often a source of interference and annoyance, and he fails to understand how, in these days of progress, a spark system can be permitted to exist. Whilst it is perhaps true that progress in marine wireless has been slow by comparison with other fields, it must be remembered that the capital invested in marine installations throughout the world is very large and, in the present depressed state of shipping, the wholesale scrapping of obsolescent plant is impracticable. Furthermore, there has been no new international legislation since the Radiotelegraphic Convention of 1912, and although the principal powers have introduced national rules to meet new technical

* *Journal I.E.E.*, 1921, vol. 59, p. 77.

conditions, there is urgent need for the co-ordination of such regulations by international agreement.

If the need for new legislation is long overdue, we have at least had the advantage of being able to gain experience in applying new technical developments to marine conditions, and in consequence it would now seem possible to legislate in a thoroughly practical manner and so ensure consistent progress at the minimum of capital loss. In this connection I should like to pay a tribute to the work of the Departments of State, in particular the General Post Office, the Board of Trade and the Services, who, through Committees on which the wireless companies are represented, are revising and redrafting our national wireless regulations.

I must ask for your indulgence if, in defiance of precedent, I now refer to some aspects of marine wireless which are of general interest. I propose to deal only with some of the more recent developments, touching on those features of design where experience gained in maintenance has shown that special precautions are necessary. I also hope to be able to show you some laboratory experiments indicating the lines on which I think future developments may take place.

Spark Sets.

Ships' spark sets are usually made in three standard sizes, $1\frac{1}{2}$, $\frac{1}{2}$ and $\frac{1}{4}$ kW, the rating being defined as the power supplied from the motor-alternator to the primary of the high-tension transformer.

In the earlier types of sets it was the usual practice to supply all the components separately and to erect the apparatus in the wireless cabin in the most convenient position, the motor-alternator and spark-gap being placed in a specially built silence cabinet.

Modern practice is to supply the transmitter components completely assembled, usually in an iron structure of the switchboard type. The advantages of this construction are :—

(1) Compactness;
(2) Less time taken to install in a ship which in some cases may be in port for only a few hours;
(3) Standardization of circuit arrangements in all ships;
(4) Ability to run full-load duration tests on each complete transmitter in addition to tests on separate component parts. This ensures that no small change in the design of a component can have an adverse effect on the working of the whole transmitter without attention being called to the fact.

From the lantern slides shown it will be seen that expanded-metal gates are employed to enclose the components. These gates are generally fitted with protective switches, the opening of a gate breaking the alternator excitation and thus avoiding risk of accidental shock when making adjustments.

The use of expanded mild steel is quite satisfactory in most cases, but care in design is necessary in regard to the distribution of the magnetic field from the high-frequency inductances, otherwise appreciable losses can be set up. In the case of the $\frac{1}{2}$kW set the losses were as much as from 30 to 50 watts; this loss was, however, reduced to a negligible quantity by using a gate of identical dimensions and mesh, but constructed in brass in lieu of mild steel. Serious losses may also occur due to the iron structure itself forming a closed loop in the vicinity of a high-frequency coil, and this must be carefully avoided in any compact design. When making tuning adjustments on any transmitter fitted with steel gates, readings on the aerial ammeter or wave-meter should always be taken with the gates closed.

Spark-Gaps and Systems of Transmission.

The principal types of spark-gap in use to-day are the synchronous gap and the quenched gap. Mr. Lea, in a paper* read before the Wireless Section in June 1922, dealt with the merits of the synchronous gap and showed that as a high-frequency generator it had an efficiency of the order of 70 per cent. He pointed out, however, that the only criterion which is of importance is the ratio of the power used to the signal strength received. In order to make a comparison on this basis some tests have recently been carried out by my company to compare the two types of spark transmission and at the same time to ascertain their merits compared with those of what is commonly called I.C.W. (interrupted continuous waves). The use of I.C.W. in the Mercantile Marine is a matter of importance, for it is the only reasonable method by which a gradual transition from the spark system to C.W. (continuous waves) can be effected without undue capital loss. In the tests referred to, transmission was carried out at Barnes on 700 m, reception being at Slough and Brentford (Middlesex). Measurements of field strength and audibility were made at the receiving stations.

Measurements of field strengths.—Dashes of 15 secs. duration were transmitted on quenched gap, synchronous gap and I.C.W. At the receiving stations the readings were recorded on a Moullin voltmeter placed across the tuned circuit of an aerial, having only a loading inductance and parallel tuning condenser. Owing to the small readings obtained on the Moullin voltmeter at Slough, due to weak field strength, it was thought that the results were not sufficiently reliable and the whole of the tests were repeated with reception at Brentford.

A type "A" Moullin voltmeter was used and, since the maximum readings did not exceed 1·5 volts, the damping due to the voltmeter may be considered to be negligible in comparison with the aerial resistance and radiation resistance. The decrement of the receiver was not accurately measured, but was observed by means of the resonance curve to be of the order 0·1.

Audibility measurements.—Morse transmission was employed and audibility measured by the simple shunted-telephone method as being the most likely to give practical comparative results. The same simple tuned circuit was employed with a crystal detector of the zincite-tellurium type, and the telephone shunt was adjusted to a point at which signals were just sufficiently audible to give accuracy of reading.

To enable a real comparison to be obtained, all

* *Journal I.E.E.*, 1922, vol. 60, p. 942.

conditions were maintained as constant as possible. Transmissions were conducted on the same day, quickly following one another. For example, quenched gap was operated for 5 minutes, immediately followed by 5 minutes of synchronous gap and 5 minutes of I.C.W.

The same motor-alternator was employed for all tests, and by careful adjustment to give good speed regulation over variations of load the note was maintained constant to within a few cycles throughout the tests.

I.C.W. was produced by means of double-wave rectification with a small feed condenser so as to give sensibly 100 per cent modulation.

TABLE 1.

Equal Power Inputs.

Type	Input power	Aerial current	Audibility factor	Field strength
	kW	amps.		volts
Quenched gap ..	1·0	4·4	1·0	0·68
Synchronous gap ..	1·0	3·4	2·3	0·39
I.C.W.	1·0	5·6	3·0	1·23

TABLE 2.

Equal Aerial Powers.

Type	Input power	Aerial current	Audibility factor	Field strength
	kW	amps.		volt
Quenched gap ..	0·83	4·0	1·0	0·57
Synchronous gap ..	1·4	4·0	3·0	0·45
I.C.W.	0·51	4·0	2·3	0·88

TABLE 3.

Equal Audibility Factors.

Type	Input power	Aerial current	Audibility factor	Field strength
	kW	amps.		volts
Quenched gap ..	7·5	12·0	1	1·7
Synchronous gap	1·4	4·0	1	0·45
I.C.W.	0·86	5·2	1	1·16

The same transmitting aerial and receiving aerial were employed in all cases.

Results.—The results are given in three tables showing comparisons of the systems with equal power imputs (Table 1), equal aerial powers (Table 2), and equal audibility factors (Table 3).

The results show the efficiency of I.C.W. over the spark systems, both for field strength and audibility (Table 1).

The audibility of quenched gap is singularly poor for the field strength (Table 2).

Table 2 shows that the synchronous gap gives good audibility with a weaker field strength than either quenched gap or I.C.W.

I.C.W. gives good field strength, good audibility and good tuning, and the same audibility (on crystal) may be obtained in comparison with synchronous spark with much less power (Table 3). If lower receiver decrements were employed, I.C.W. should give even better results on account of its sharper resonance curve.

From Table 1 it will be seen that, power for power, a larger aerial current is obtained with quenched gap than with synchronous gap. This is of especial interest in view of a regulation recently introduced by the Post Office basing the range of ships' stations upon the metre-ampere standard. This regulation is very convenient for ship-inspection purposes, but, by ignoring the factors of audibility and tuning, it definitely favours the adoption of quenched gap, particularly on the smaller class of ship having low masts and low-power sets.

I am fully aware that some of these results are directly contrary to the generally accepted view that I.C.W. gives poor audibility with crystal reception, but with the exception of some data given by Mr. Shaughnessy in his Chairman's Address * to this Section in 1923 very few actual results seem to have been published.

Whilst the greatest care was taken over the tests, they may be a little unfair to the quenched-gap system, as it is probable that this type of transmitter was not working quite up to its maximum efficiency, and although the figures may be relied upon to within 10 per cent the tests have not been repeated as frequently as in my opinion is generally desirable. The matter is of great importance, not only from the point of view of marine communications, but also for reasons of safety of life at sea.

All ships now fitted with C.W. installations also carry spark sets, and more information is urgently needed as to whether I.C.W. can be relied upon to carry out all the functions of a spark transmitter, bearing in mind the receiving conditions aboard other ships. If the results given do nothing more than cause others to investigate this matter more closely, they will have proved of some value.

EMERGENCY SETS.

Regulations require that an independent source of power be supplied for operation of the wireless set in the event of the failure of the ship's main electric supply in times of emergency. It is still almost universal practice to supply a battery for this purpose, owing to the difficulty of producing a prime mover of the internal-combustion type which can be guaranteed to start quickly under all conditions met with at sea. The accumulator battery, however, is expensive to install and maintain and, due to the irregular manner in which it is used, often standing idle for long periods, deterioration is fairly rapid. With the lead–acid type an average life of about three years is all that can be expected. Nickel–iron batteries are now being tried in lieu of the lead type, and it is hoped that they will stand up better to sea conditions.

* *Journal I.E.E.*, 1924, vol. 62, p. 51.

It is possible that in the future a satisfactory type of internal-combustion engine will be developed for this purpose, though at the present time insurance companies and shipowners object to the use of petrol aboard ships, and this increases the difficulties of producing an engine which can be relied upon to start quickly. Electric starting would again introduce the objectionable features of the battery, although this could be of a smaller capacity than the usual emergency batteries now supplied. As the engine employed need not exceed 2 h.p., there would seem to be possibilities in the development of a reliable mechanical starter of either the spring or foot-pedal type; preferably the design should be such that the engine could be started without the operator leaving his seat.

It is usual to employ the same high-frequency circuits for both power and emergency purposes, though with synchronous spark sets an emergency fixed spark-gap is usually employed. In very large liners having high masts and a long aerial span there is greater risk of the aerial being carried away in a storm, and it is customary to provide an emergency aerial fixed on outriggers to the funnels.

For a number of years the radio-frequency circuits were excited by means of a spark coil driven from the battery. Such an arrangement is, however, not efficient, and the signal note produced is of such low frequency that reception is difficult under conditions of interference. This matter is of considerable importance in connection with the operation of automatic watch-keeping devices, which, experience has shown, cannot be depended upon when a low spark frequency is employed. It is probable that future legislation will fix a minimum note frequency for emergency installations.

Higher spark frequencies of, say, 850 per sec. may be obtained with a rotary interrupter, transformer and tuned musical circuit. A rotary interrupter, however, is somewhat troublesome to maintain in good order, even when the musical circuit is carefully designed to reduce sparking to a minimum; the most modern practice is to employ a 500-cycle motor-alternator driven from the battery. This arrangement, although more expensive, is certainly to-day the most satisfactory form of emergency equipment.

Lifeboat Installations.

Legislation has recently been introduced for the compulsory fitting of wireless sets of the spark type to ships' lifeboats. The more important considerations in the design of such apparatus are:—

(1) Weatherproofness;
(2) Simplicity and ease of manipulation;
(3) Light weight and small dimensions;
(4) Technical considerations such as endurance, prime mover, insulation, etc.

(1) *Weatherproofness.*—This may be secured by installing all the component parts in a small cabin which, to be effective, should be of sufficient size to accommodate the operator. It is, however, obviously difficult to fit a cabin of this nature in an open boat without seriously encroaching on passenger space. The alternative method is to encase the entire transmitter and receiver with all controls and switchgear in a watertight case of small dimensions, operation being effected through a small hole which may be fitted with a watertight sleeve.

(2) *Simplicity and ease of manipulation.*—In an emergency it is not possible to ensure that a qualified wireless operator will be available in the lifeboat. The set must therefore be so designed that it can be operated by any seaman or ship's officer having only a knowledge of the Morse Code.

(3) *Weight and dimensions.*—In the set illustrated in the lantern slides the dimensions of the watertight case containing all the wireless apparatus are 25 in. × 12 in. × 17½ in., and the weight is 65 lb. The total weight with nickel–iron battery and motor-alternator is 370 lb. If a lead battery of equivalent capacity is used, the weight of the battery only is 400 lb.

(4) *Technical considerations.*

Prime mover.—There is still a wide difference of opinion as to whether the petrol engine or the storage battery is the more suitable for the power supply of lifeboat sets, and the point is not likely to be settled until some experience is gained of the behaviour of lifeboat sets under actual emergency conditions.

Weight for weight, more power can be stored in the form of petrol than as electrical energy in a battery, but against the petrol engine is the probable difficulty of starting up in cold weather and under shipwreck conditions, and also the necessity for stopping the engine during the periods of reception. In any case, some batteries must be supplied for operating the filaments and high-tension supply of the valve receiver.

Driving the motor-alternator from a battery of the nickel–iron type is probably the simplest proposition. The battery can be more easily protected from spray and may be stowed under the thwarts out of the way of passengers.

Arrangements must be made for charging the battery in situ from the ship's mains by means of a flexible lead to a plug socket near the lifeboat davits.

The Board of Trade regulations specify that the battery shall be of sufficient capacity to provide for transmission of morse signals for 6 hours continuously with a power of 15 metre-amperes in the aerial. The accepted definition of "morse" load is 60 per cent of the increase in load produced when the key is pressed.

In the set illustrated in the lantern slides the average current at 18 volts taken by the motor running light is 11 amperes and the "key down" full-load current 22 amperes. The required battery capacity for 6 hours' morse transmission is therefore $\{11 + 0 \cdot 6\,(22 - 11)\} \times 6 = 105 \cdot 6$ ampere-hours. The battery supplied is 18 volts, 120 ampere-hours, at the 6-hour rate. If a searchlight is also fitted, the capacity must be increased to 140 ampere-hours.

The main battery is also used for supplying filament and high-tension current for the valve receiver.

Transmitter circuits.—The quenched-gap system is unquestionably the most suitable for lifeboat sets. The circuits can be simple and auto-coupled, and the

gap needs no adjustment and is unaffected by moderate variations in alternator speed.

The Board of Trade regulations require only one wave, viz. 600 m, with 15 metre-amperes in the aerial. The primary circuit can therefore be permanently tuned to the wave, and the aerial is most conveniently tuned in by means of a variometer, an aerial ammeter being employed to indicate the correct tune.

The height of a lifeboat aerial averages 6 to 7 metres; hence to obtain 15 metre-amperes an aerial current of not less than 2·5 amperes is required. To attain this current in a very small aerial (the average capacity is 0·00019 μF) very high potentials are necessary, and these considerably increase the insulation difficulties under wet conditions. The aerial potentials (crest value) measured under working conditions are of the order of 40 000 volts.

To test the efficiency of the lead-in insulator, salt water was poured over the set while in operation; the aerial current soon fell from 3 to 2 amperes and steam began to rise from the canvas-covered wood immediately surrounding the lead-in insulator. Ultimately the wood dried and charred. These difficulties were overcome by fitting a large metal cowl over the insulator and a flat earthed plate of similar diameter over the woodwork surrounding the insulator. The guard-ring effect of this arrangement reduces the electrical stress, and the set proved quite satisfactory in operation when drenched with sea water.

Receiver circuits.—Reception conditions in an open boat in stormy weather and with a poor aerial are likely to be very difficult, consequently valve amplification is essential.

A detector valve followed by two stages of low-frequency amplification gives a simple arrangement entailing no filament rheostats or other adjustments.

If dull-emitter valves of the peanut type are employed, the filament current can be supplied from a single cell of the main nickel-iron battery (1·2 volts), the entire battery of 18 volts being used for the high-tension supply. High-tension batteries of the dry-cell type deteriorate too rapidly, when not in use, to be depended upon.

Since under "S.O.S." conditions extreme selectivity is of no importance, the detector may be connected directly across the transmitting variometer. A single adjustment then provides for the tuning of both transmitter and receiver. The closely coupled transmitter primary circuit does not damp the aerial circuit when receiving, as it is interrupted by the spark-gap. With the correct design of variometer the receiver can be tuned from 550 to 650 m on all aerials whose capacities lie between 0·000125 μF and 0·000250 μF.

General Characteristics of Ships' Aerials.

On account of the varying types of aerials fitted to ships, the disturbing effects produced by the ship's rigging, and the uncertain character of the path to earth from the wireless cabin, this subject can only be treated in a general manner based on data obtained from the tuning curves of several hundred ships.

The T aerial is most generally employed and is usually convenient as regards the disposition of the down-lead clear of other rigging. This form of aerial also enables a lower natural wave-length to be obtained without appreciably reducing the wave-length obtainable when the maximum loading inductance is of the order 300 μH.

Except in special cases, multi-wire aerials are undesirable, the latter being subject to the following disadvantages:—

(1) More complicated to rig and keep in order.
(2) The reduction in conductor losses is usually so small as to be unimportant in relation to other losses.
(3) The insulation losses are usually greater, due to a number of insulators being placed in parallel, since it is undesirable to employ insulators for holding up the spreaders.

Most ships' aerials in use to-day are of either the twin or single-wire type. The latter is coming largely into favour for the reason that, having no heavy spreaders, the inertia and wind forces are less. For single-wire aerials it is usual to employ a special type of heavily galvanized steel wire with a hemp core. A large number of tests at sea have been carried out to obtain a comparison between the twin copper-wire aerial and the single steel wire, and although with the latter the aerial current obtained is less, there seems to be no drop in signal range.

Regulations still provide that all ships shall be capable of transmitting on 300 m; the natural wave-length of aerials in large ships often exceeds this figure, consequently it is necessary either to provide a series condenser or to split the aerial and lead in the two down-leads separately. This latter method involves the use of an additional lead-in insulator, the cost of which is approximately the same as that of a series condenser. The expenditure in either case is wasteful, since the efficiency of such arrangements is poor, and in practice 300 m is rarely, if ever, used by large and medium-sized vessels. The continuance of this regulation is therefore very undesirable.

The application of the rough formula for the calculation of the natural wave-length of a T aerial, viz.

$$\lambda_0 = 4(H + \tfrac{1}{2}l) \text{ metres}$$

is by no means accurate for ships, owing to the disturbing effects of the rigging.

Tuning data obtained from a large number of ships all having a uniform type of aerial-tuning inductance indicates that the following approximate constants in the formula are more nearly correct:—

Twin T aerials $\lambda_0 = 5\cdot 2(H + \tfrac{1}{2}l)$ metres
Single T aerials $\lambda_0 = 4\cdot 6(H + \tfrac{1}{2}l)$ metres

where H is the height from the water line and l the aerial span.

It is impossible to estimate accurately the capacity of ships' aerials even by the aid of an empirical formula, owing to the many disturbing factors, but it is found in practice that the long-wave (static) capacities of T aerials in merchant ships vary from 600 to 1 300 cm

in the case of twin wires and 500 to 650 cm in the case of a single wire.

In most cases the effective capacity at the natural wave-length is about half the long-wave capacity.

Aerial insulators.—Three types are in general use:

(*a*) Rubber strop;
(*b*) Porcelain rod;
(*c*) Porcelain chain (various forms).

The rubber strop has far too great a dielectric loss to be used on ships fitted with C.W. It deteriorates rather rapidly in the tropics, or if in the vicinity of hot gases from the funnels, but being flexible it is not easily broken and is very convenient for use on those cargo ships where the aerial must be lowered to work the derricks. Strop insulators have been known to fail under torsion, due to the pull on a twisted aerial wire or halyard.

Straight porcelain rods are less expensive, but are only satisfactory for C.W. work if fitted with drip-rings. In the event of fracture due to overload in heavy weather the falling porcelain is a real source of danger, and although in practice no actual injury to passengers or crew has occurred, some narrow escapes have caused my company to abandon the use of this type of insulator.

The porcelain-chain type of insulator, if carefully designed, is probably the most satisfactory for marine purposes, though it is heavier and more expensive than either the porcelain rod or strop. It is mechanically very strong and safe in use, and with a properly designed chain the losses when employing a 1½-kW C.W. set should not exceed 15 watts on the most difficult wave-length and with the insulator sprayed with water, making the equivalent of a heavy tropical rain.

Automatic Call Devices.

The maintenance of a continuous watch aboard ship is important from the point of view of safety of life at sea. Since, however, a continuous watch necessitates the employment of three operators, the expense is prohibitive on the smaller class of vessel conducting only a very limited amount of wireless telegraph traffic.

The regulations under the Merchant Shipping (Wireless Telegraph) Act, 1919, made provision for the possibility of the development of a reliable automatic watch-keeping device capable of ringing an alarm bell on the receipt of a distress signal.

The introduction of a call device would effect a considerable economy to the shipowner, and apparatus of this character has been under almost continuous development since 1920.

Attempts were made to construct apparatus capable of responding to the distress signal (S.O.S.) and the ship's own call sign, but after a number of tests at sea and ashore it soon became apparent that any apparatus operating on the Morse Code was too susceptible to interference to be approved as reliable from the point of view of safety of life at sea.

During 1923 and 1924 the Admiralty, at the request of the Board of Trade, conducted a series of tests with calling appliances submitted by the Post Office, the Marconi Company and the Radio Communication Company, with a view to ascertaining what, in principle, is the most satisfactory form of signal and apparatus.

Full details of these trials were recently published in a White Paper entitled "Report by the Admiralty on Tests of Automatic Wireless Calling Devices." Generally, the results of these trials demonstrated that the long-dash call gave too many false calls and that the most suitable form of signal consisted of a series of dashes of 4 seconds each, separated by an interval of 1 second, and that it should be possible to develop apparatus to register 90 per cent effective calls.

A description of one of the appliances used in these tests, and subsequent improvements thereon, may be of general interest. The telephone terminals of the receiver are connected to a note amplifier, and the amplified current is then rectified a second time and passed to a sensitive relay of the moving-coil type. The tongue of this relay therefore follows all incoming signals, whether morse or the special signal it is desired to receive and select.

The timing element of the selector consists of a very simple form of electric motor, the armature comprising a simple iron bar without any windings. The speed is controlled by a governor of the gramophone type. The motor drives a magnetic clutch through a reduction gearing, the speed of the clutch shaft being 2 revs. per min. When the magnetic clutch closes, it drives an extension shaft on which the selecting cam mechanism is mounted, and if the signal be of the correct type the clutch is held closed until a final cam operates a contact which rings the alarm bell. If, however, the signal is incorrectly timed, the selector mechanism breaks the clutch circuit and the cam is instantly reset to the zero position by means of a spring.

The selector mechanism is necessarily of a somewhat complex nature and is shown diagrammatically in Fig. 1. All the selector cam contacts are cut on a single circular disc, but for purposes of clarity they have been shown as straight strips which, on the commencement of operations, we must imagine all advance upwards and together, and open or close contact with the contact points E, F, G, M and J. It will be seen that the alarm-bell contact is the last of the series and can only operate if the entire cam mechanism advances to the end of the series of operations, i.e. the bell only rings if the signal conforms to the correct timing as shown on the time scale. This is accomplished in the following manner: On the commencement of the first dash the tongue of the sensitive relay moves over to "mark" (contact M), and current from the battery excites the clutch relay coil CR through the contacts G and F, whose functions will be explained later. The relay CR then closes contacts A and B, the latter completing the magnetic clutch circuit, and all the cams commence to advance (upwards in the figure). Now, after 3 seconds, contact E closes; this is in parallel with the "mark" contact of the sensitive relay, so that if during the period E is closed, a space in the signal occurs, as it should do, between the fourth and fifth seconds, the relay CR will not be opened, and contacts A and B remain closed, the latter exciting the clutch, and the cams continue to advance.

But how are we to know that a space has occurred during the period when contact E is closed, for the apparatus must not be capable of responding to a continuous dash? This is accomplished by means of the space test cam, the contact G and the space relay SR. If the "tongue" of the sensitive relay has touched the space contact S, even only momentarily, in the period 3–6 seconds during which time contact E is closed (as it should do with the correct signal), then the space relay SR closes contacts C and D. Now contact C is in parallel with the "space" contact on the sensitive relay, consequently a momentary closing of the former causes the space relay SR to

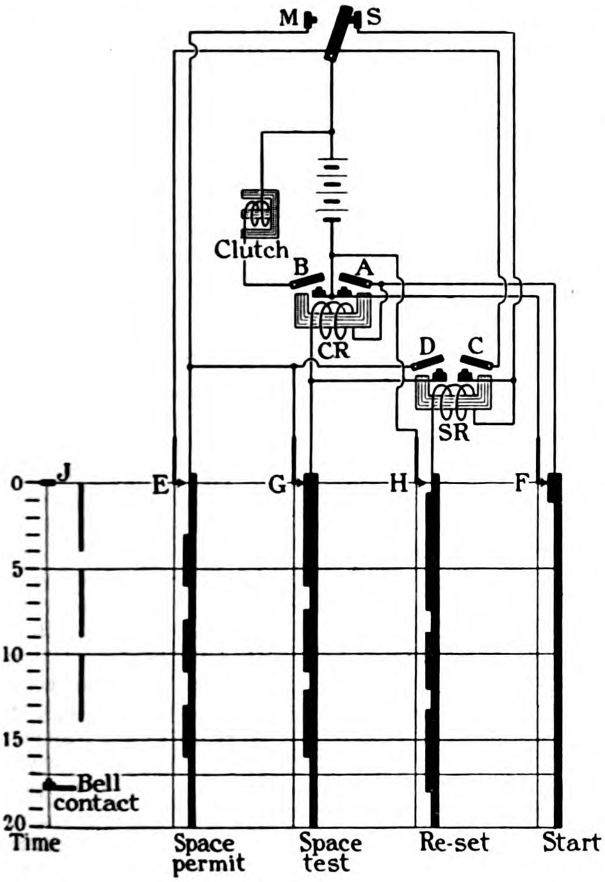


FIG. 1.

remain closed. Before the end of the 6th second, therefore, the space relay should have become "set" closed if a space has occurred, and this must now be checked. This is done by the space test cam which, after the sixth second, opens the contact G. This contact G is in parallel with the contact D of the space relay; if D is closed, as it should be, then the opening of G makes no difference, but if D is not closed, i.e. if a space has not occurred in the signal, then the opening of contact G breaks the excitation of the relay CR. A and B open, the clutch is demagnetized and all cams reset to zero position by the action of a spring.

After testing, if a space has occurred in the manner described, it is necessary to reset the space relay SR so as to be ready to carry out its space-testing functions during the 8th to 11th seconds, and this is accomplished by means of the re-set cam which opens the contact H, so de-exciting the relay SR, contacts C and D then opening to normal position. This cycle of operations is then repeated for the second and third dashes until the alarm-bell contact is ultimately closed.

Now it is important that if an incorrect or badly timed signal is received the whole mechanism should re-set instantly to zero, and it must not be capable of being restarted at an intermediate position, as might occur if the "mark" contact of the sensitive relay were closed while the apparatus was resetting to zero. This is prevented by means of the start cam which opens the contact F as soon as the cams have started to advance. Contact F is in parallel with the sustaining contact A, which, as we have seen, opens if there is anything wrong with the signal. The relay CR can only be re-excited for the purposes of restarting operations if the contact F is closed, and this cannot occur until the entire cam mechanism has returned to zero.

It will be noted that in the cutting of the cams there is a certain amount of latitude to allow for slight inaccuracies in sending. For example, the dashes may be clipped by a second at either end and a space may occur anywhere between the 3rd and 6th, the 8th and 11th, and the 13th and 16th seconds. Latitude of this character tends to increase the chances of false calls, though, with the degree of latitude shown, an average of only 1 false call in 500 was registered in the Admiralty trials, and this may be considered quite satisfactory.

The fact that the shortest space suffices and that spaces up to 3 seconds may be made, tends to minimize the liability of failure from interference by jamming signals and atmospherics.

Direction-Finding.

The modern tendency in the Mercantile Marine is to adopt small multi-turn loops, either fixed or revolving, in place of the larger single-wire triangular loops formerly employed. It is obviously possible to secure small loops in a more rigid manner, and, as they need not be disturbed when handling cargo, errors due to any deformation of the aerial system are avoided.

Direction-finding as applied to the Mercantile Marine has already been very well dealt with in papers read before this Section, and I propose only to describe some improvements which have recently been made to the Robinson system. In this system two coils are fixed rigidly at right angles to one another and revolve about a vertical axis. One coil called the "main coil" has a smaller number of area turns than the second coil, usually called the "auxiliary coil." The coils are connected in series, and by means of a switch the sense of the auxiliary coil in relation to the main coil can be reversed. By revolving the whole system, points may be obtained where, on operating the reversing switch, signals are found to be of equal strength in either position of the switch. Two such points 180° apart are sharp and well-defined and indicate the correct bearing, but there are also two points 90° to the correct bearing where a balance can

be obtained, though less well-defined. In unskilled hands, therefore, this 90° ambiguity may be a source of danger unless a preliminary observation be made on the main coil only, and a special switch is usually provided to cut out the auxiliary coil for this purpose. The reason for this 90° ambiguity will be seen by studying the E.M.F.'s induced in the coils by the incoming signal and the angle between the plane of of the main coil and the direction of the signal. This is shown in Fig. 2 for the main coil and in Fig 3 for the auxiliary coil. The scale of E.M.F.'s is purely arbitrary,

the signals are loudest. The auxiliary coil is then brought into use and the accurate balance obtained.

I now propose to describe a new device designed to obviate the necessity for any preliminary observation. In this arrangement the reversing switch and operating handwheel are mechanically interconnected. The handwheel is no longer rigidly connected to the spindle carrying the coils, but drives the coils through a coupling permitting a certain amount of backlash * (say 1° of arc).

The relative motion of the handwheel and shaft

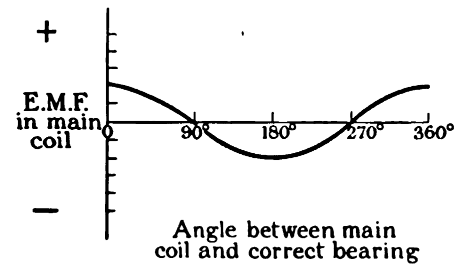


Fig. 2.

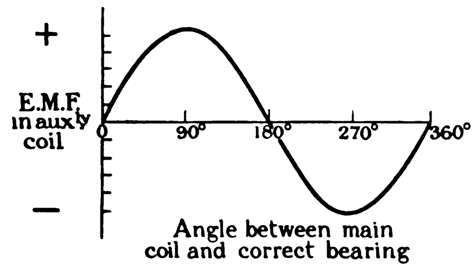


Fig. 3.

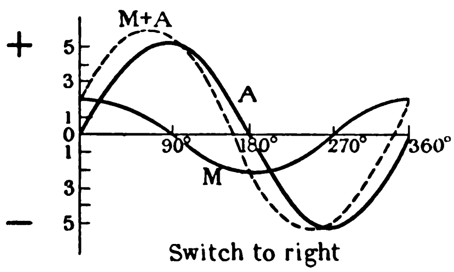


Fig. 4.

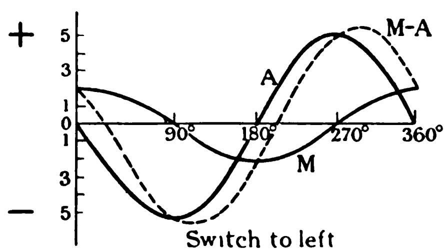


Fig. 5.

but as the auxiliary coil has a greater number of area turns the E.M.F. amplitude has been shown greater. The two coils are connected in series through a reversing switch, and if we suppose that in the right-hand position of the switch the E.M.F. in the auxiliary coil assists those in the main coil, we shall obtain the dotted curve ($M + A$) in Fig. 4, which represents the resultant E.M.F. from the algebraic sum of the E.M.F.'s of the two coils.

Now if the switch is moved to the left the auxiliary coil will now oppose the main coil, and we can represent the resultant E.M.F. by turning the curve for the auxiliary coil upside down (Fig. 5).

Now if we assume that the strength of signal is roughly proportional to the numerical value of the E.M.F., we can draw two new curves (Fig. 6) showing the strength of signal with the reserving switch to left or right. The points of balance are where the curves intersect (Fig. 6) at 0°, 90°, 180° and 270°. The correct balance, i.e. that obtained when the plane of the main coil is in the direction of the distant station, is at 0° or 180°, the incorrect balance (90° out) being at 90° and 270°. It can be seen from the slope of the curves that a sharp balance will be obtained at 0° and 180°, and an ill-defined balance when 90° out. To obviate this ambiguity a preliminary observation is usually made on the main coil only, the system being rotated until

is utilized to operate the reversing switch. If the leads to the switch are connected in the correct sense the device will operate in the following way: The signal from the distant station is heard on the telephones, and the handwheel moved to and fro to the extent of the backlash. This operates the reversing switch. Generally, the two positions give unequal signals.

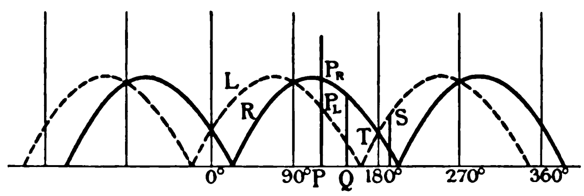


Fig. 6.

The operator is told to turn the handwheel in the direction giving the weaker signal, and to continue turning it in that direction, thus turning the whole system. We see that he then is driven away from the "90° out" bearing towards the "correct" bearing. After he has turned a few degrees he again moves the handwheel to and fro and judges the relative signal

* This backlash in no way affects the accuracy of bearings, since the indicator dial and coils are rigidly fixed on the same shaft.

strength. He again rotates the system in the direction corresponding to the weaker signal, and after a few attempts gets a balance. The "correct" bearing is now indicated by the pointer on the dial.

The reason for this is as follows: Referring again to Fig. 6, suppose that at the beginning of the operation the angle between the coils and the transmitter is given by the point P. The ordinate at P cuts the curves L and R at P_L and P_R, and P_RP is greater than P_LP, or, in other words, the signal is weaker with the wheel turned to the left. In accordance with the rule the system is turned more to the left, say to Q. The balance is tested again and the wheel is moved more to the left, say to S. Here S_L is greater than S_R. The signal is weaker with the wheel to the right. The system is turned to the right, and so on, until the correct balance is obtained at T.

It will be seen that each operation takes the system further away from the "90° out" position, and so completely eliminates the latter.

Visual indication.—Any aural system depends to some extent on the personal element, and in consequence varying results may be obtained. The system at present, only in experimental form, has been devised to give a direct *visual* indication of the balance. The method is based on the principle that when an alternating current with a small direct current superimposed on it is passed through a d.c. moving-coil galvanometer of sufficiently slow period, the galvanometer will show the value of the direct current and, more particularly, will show when it reaches a zero value.

The standard Robinson system is used, but the reversing switch is replaced by a special motor-driven commutator. This commutator has two functions: (1) To reverse the relative connections of the main and auxiliary coils; and (2) to reverse the rectified output from the amplifier to the galvanometer in synchronism with (1).

If we suppose first that the commutator is at rest and the coil system is in the position of balance, and that a signal is being received, the galvanometer will show a deflection of, say, 10° due to the rectified signal current from the amplifier. On turning the commutator through 180° the "Robinson" reversal is carried out, and the current through the galvanometer is also reversed. Since we supposed that the coil system was in the position of balance, the galvanometer will again read 10° in the opposite direction.

If the commutator is now run sufficiently fast, the galvanometer will not be able to follow the alternation of direction, and will stay at zero.

If we now suppose that the coil system is turned so that the balance is not obtained, the galvanometer will receive more current in one direction than the other, and will be deflected from zero. It will therefore be seen that if the coil system is rotated until the galvanometer pointer is at zero, the coil system is indicating either the correct or the "90° out" bearing.

How are we to eliminate the "90° out" bearing? This is done in a way similar in principle to the device just described, namely, by correlating the movement of the galvanometer pointer with the movement of the operating handwheel. The galvanometer is preferably placed so that its pointer when on zero lies on a line passing through the centre of the coil spindle and points outwards. If the galvanometer is connected up in the right sense the following rule will avoid the "90° out" bearing. Turn the handwheel in such a direction that if the galvanometer pointer were imagined as being connected mechanically to the direction-finding coils, this direction of rotation would bring the pointer towards zero, i.e. if the pointer is to the *left* of zero, turn the handwheel to the *right.*

The great advantage of the visual indicator method is the speed with which really accurate bearings may be taken, and that little or no previous practice is necessary. In the case of a man who has never worked a direction-finding set before, the galvanometer method will give an accuracy of $\pm \frac{1}{4}°$ compared with $\pm$ 2° or 3° by the aural method. This system therefore is well suited for installation on the bridge or in the chart room of a ship, where it may be operated by the navigating officer.

Automatic direction-finding.—By replacing the galvanometer by a sensitive relay of the moving-coil type a series of interesting developments are possible. The relay may be made to light one of two lamps, say, red or green, showing whether the coil system is to be turned to port or starboard. In aircraft employing fixed coils an indicator of this character should prove of value in enabling the pilot to "home" on a ground station by watching two lamps on his dashboard. If the relay is made to operate a reversible motor or a magnetic clutch mechanism with a reversing gear, the direction-finding coils can be made to turn automatically in the direction of the correct bearing and, assuming that the connections of the driving mechanism have been correctly arranged, the coils will always move automatically away from the "90° out" bearing. I hope to be able to demonstrate this now by experiment.

It may be argued that any system dependent on a visual indicator, whether operated by hand or automatically, can have little practical application, on account of the erroneous bearing which would result from interfering signals.

The accuracy of any direction-finding observations is affected by interference, but in the case of aural methods any interference is at once apparent to the operator.

In the case, therefore, of any visual indicator or automatic system, it would be necessary to provide also an aural indicator which, in the case of a ship's installation, might take the form of a loud-speaker, in order that the observer may know if any interference is present and also for the purpose of identifying the transmitting station whose bearing is being observed.

I believe, however, that when an efficient system of I.C.W. beacon stations is introduced, operating upon a wave-length of 1 000 m, troubles from interference will largely disappear, particularly as ranges in excess of 50 miles are not generally required.

I feel somewhat diffident in making any forecasts of developments of this character, but let us try to visualize the situation on the bridge of a ship navigating

near the coast in thick weather, and let us also imagine an automatic direction-finder installed with a loud-speaker indicating the periodic signals of a beacon station. Almost simultaneously with the call of the beacon the pointer on the direction-finder moves to the correct bearing and the commander may see at a glance how the bearing is altering as he proceeds on his course.

I should like, in conclusion, to express my indebtedness to Mr. Lea and Mr. Bainbridge-Bell for their assistance in connection with the experiments I have been able to show this evening.

INSTITUTION NOTES.

Honorary Member.

At the Ordinary Meeting held on the 5th November, 1925, the President announced that the Council had elected Dr. S. Z. de Ferranti an Honorary Member of the Institution.

List of Members.

Copies of the new List of Members (corrected to the 1st September, 1925) are now ready, and any member wishing to receive a copy should apply to the Secretary.

Associate Membership Examination Results: October, 1925.

Passed.

Bainbridge, S. R. (Sunderland).
Braendle, E. W. (London).
Cain, S. J. (Lutón).
Dennison, J. D. (Wotton-under-Edge).
Dick, R. (Penicuik).
Drummond, C. W. B. (Eastbourne).
Forster, W. J. (Stoke-on-(Trent).
Greenwood, E. R. (Douglas, I.O.M.).
Greenwood, H. J. (Manchester).
Hall, M. H. (Sheffield).
Hands, H. F. (Sutton Coldfield).
Harmer, L. B. (London).
Hodgson, C. H. (Crewe).
Hollin, A. S. (Bradford).
Hortop, C. L. (Southampton).
Ingamells, G. H.(Grimsby).
Jewell, E. H. T. (London).
Linsell, A. A. (Brentwood).
McMillan, D. (Newcastle-on-Tyne).
Orchard, F. C. (Birmingham).
Pank, J. C. (Norwich).
Phoenix, W. (Warrington).
Platt, E. (St. Helens).
Price, J. M. (Birmingham).
Rigg, R. (Glasgow).
Shepherd, J. H. (Manchester).
Stretton, L. W. (London).
Sykes, P. (Manchester).
Taylor, L. N. (Chislehurst).
Tumilty, H. G. (Dovercourt).
Waring, A. J. (Torquay).
Weller, B. F. (London).
Winwood, W. (Coalville).
Yorke, G. (London).

Passed Part I only.

Rogans, T. H. (Liverpool).
Stewart, C. E. (London).
Taylor, J. (Darwen).
Tyacke, N. A. (Chichester).

Passed Part II only.

Aust, J. H. (Stoke-on-Trent).
Grepe, F. Y. (London).
Hawkins. E. J. (Braintree).
McGrath, T. (London).
McNicholl, J. G. (Maghera, Co. Derry).

Further results relating to candidates who sat for the Examination abroad will be published later.

National Certificates and Diplomas in Electrical Engineering.

The following Institute and College have been approved under the scheme drawn up by the Board of Education and the Institution : —

Approved for Ordinary Grade Certificates (Senior Part-time Course).

Northampton Polytechnic Institute, Clerkenwell, E.C. 1.

Wednesbury, Staffs, County Technical College.

Approved for Higher Grade Certificates (Advanced Part-time Course).

Northampton Polytechnic Institute, Clerkenwell, E.C. 1.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 October–25 November, 1925 :—

	£	s.	d.
Anonymous		5	0
Blackiston, H. E. (London)		5	0
Evans, R. L. (Shanghai)		6	6
Farrer, M. (Twickenham)		5	0
Hills, R. (Cromford, Derbyshire)		10	0*
Lamb, H. C. (Manchester)	2	2	0
Line, W. J. (Birmingham)		5	0*
North-Midland Centre	8	2	6
Taylor, V. A. (Wolverhampton)		5	0*
The " 25 Club "	21	0	0
W. T. Henley's Telegraph Works, Ltd.	25	0	0

* Annual Subscriptions.

Committees 1925–26.

Among the Committees appointed by the Council for 1925–26 are the following :—

Informal Meetings Committee.

The President.

Mr. A. H. Allen.	Mr. A. G. Hilling.
Mr. J. W. Beauchamp.	Mr. C. L. Lipman.
Mr. J. Coxon.	Mr. W. Riggs.
Mr. P. Dunsheath, O.B.E., M.A., B.Sc.	Mr. M. Whitgift.
	Mr. H. T. Young.

Lt.-Col. K. Edgcumbe, R.E. (T.A.) (representing the General Purposes Committee).
The Chairman of the Papers Committee.
The Chairman of the London Students' Section.

Library and Museum Committee.

The President.

Col. R. E. Crompton, C.B.	Mr. S. W. Melsom.
Major E. O. Henrici, R.E. (Ret.).	Mr. W. M. Mordey.
	Mr. R. W. Paul.

Col. T. F. Purves, O.B.E.

Local Centres Committee.

The President.

Mr. B. A. M. Boyce.	Prof. Magnus Maclean, D.Sc., LL.D., F.R.S.
Mr. J. W. Burr.	Mr. A. E. Malpas, Wh.Sc.
Sir J. Devonshire, K.B.E.	Mr. F. J. Moffett, B.A.
Mr. E. Edwards.	Mr. W. F. Mylan.
Mr. A. G. Ellis.	Mr. A. Page.
Lt.-Col. K. Edgcumbe, R.E. (T.A.)	Col. T. F. Purves, O.B.E.
Mr. R. W. Gregory.	Mr. J. H. Shaw.
Mr. J. S. Highfield.	Mr. J. S. Thomson.
Mr. S. D. Jones.	Mr. S. J. Watson.

Mr. W. B. Woodhouse.

"Science Abstracts" Committee.

The President.

Mr. Ll. B. Atkinson.	Mr. W. M. Mordey.
Mr. F. Gill, O.B.E.	Mr. C. C. Paterson, O.B.E.

Dr. D. Owen .. Mr. T. Smith ..	Representing the Physical Society of London.

Ship Electrical Equipment Committee.

The President.

Mr. A. G. S. Barnard.	Mr. N. W. Prangnell.
Mr. J. H. Collie.	Lt.-Col. A. P. Pyne.
Mr. B. M. Drake.	Mr. P. Rosling.
Mr. A. Henderson.	Mr. S. G. C. Russell.
Mr. J. W. Kempster.	Mr. T. A. Sedgwick.
Mr. J. F. Nielson.	Mr. H. D. Wight.

And	*Representing*
Sir W. S. Abell, K.B.E. .. .. Mr. H. Ruck Keene	Lloyd's Register of Shipping.
Mr. T. Carlton ..	Board of Trade.
Mr. W. Cross ..	Electrical Contractors' Association.
Mr. J. Foster King	British Corporation for the Survey and Registry of Shipping.
Mr. J. Lowson ..	Institution of Engineers and Shipbuilders in Scotland. Electrical Contractors' Association of Scotland.
Mr. A. W. Stewart	Institution of Naval Architects.
Mr. H. Walker, O.B.E.	N.E. Coast Institution of Engineers and Shipbuilders.

Wiring Rules Committee.

The President.

Mr. Ll. B. Atkinson.	Mr. P. V. Hunter, C.B.E.
Mr. H. J. Cash.	Mr. S. W. Melsom.
Mr. A. C. Cockburn.	Mr. J. F. Nielson.
Mr. J. R. Cowie.	Lt.-Col. A. P. Pyne.
Mr. W. Cross.	Mr. E. Ridley.
Mr. J. Frith.	Mr. S. G. C. Russell.
Dr. C. C. Garrard.	Mr. C. P. Sparks, C.B.E.
Mr. R. Grierson.	Mr. A. L. Taylor.

And	*Representing*
Mr. B. M. Drake ..	Contractors (unofficially).
Sir T. O. Callender Mr. J. F. W. Hooper	Cable Makers (unofficially).
Mr. J. Howard Blood Mr. E. B. Hunter .. Mr. W. B. Trafford	Fire Offices Committee.
Mr. E. G. Batt .. Mr. H. H. Berry .. Mr. J. R. Dick .. Mr. A. R. Everest .. Mr. C. Rodgers, O.B.E., B.Sc., B.Eng.	British Electrical and Allied Manufacturers' Association.
Mr. W. F. Bishop..	Cable Makers' Association.
Mr. F. R. Baldock	Independent Cable Makers' Association.
Mr. W. R. Rawlings Mr. S. H. Webb ..	Electrical Contractors' Association.
Mr. R. A. Ure ..	Electrical Contractors' Association of Scotland.
Mr. O. M. Andrews	Conference of Chief Officials of the London Electric Supply Companies.
Mr. E. T. Ruthven Murray	Incorporated Association of Electric Power Companies.
Mr. J. Christie .. Mr. F. W. Purse ..	Incorporated Municipal Electrical Association.
Mr. F. T. Alldread	Association of Supervising Electricians.

Wireless Section.

The Committee of the Wireless Section for 1925–26 is constituted as follows :—

Major B. Binyon, O.B.E., M.A. (*Chairman*).

The President.

Mr. R. C. Clinker.
Mr. P. R. Coursey, B.Sc.
Mr. C. F. Elwell.
Professor C. L. Fortescue, O.B.E.
Professor G. W. O. Howe, D.Sc.
Captain N. Lea, B.Sc.
Mr. C. F. Phillips.
Captain H. J. Round, M.C.
Commander J. A. Slee, C.B.E., R.N.
Mr. E. H. Shaughnessy, O.B.E.
Mr. C. F. Trippe.
Mr. L. B. Turner, M.A.

Mr. F. Gill, O.B.E. (representing the Council).

Colonel T. F. Purves, O.B.E. (representing the General Purposes Committee).

The Chairman of the Papers Committee (*ex-officio*).

And	*Representing*
Commander G. C. Candy, O.B.E., R.N.	Admiralty.
Major A. G. Lee, M.C., B.Sc. ..	Post Office.
Lt.-Col. H. P. T. Lefroy, D.S.O., M.C.	Air Ministry.
Major H. C. B. Wemyss, D.S.O., M.C.	War Office.

Representatives of the Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies, and the dates on which they were appointed :—

Birmingham Chamber of Commerce :
Mr. S. T. Allen (27 Mar., 1919).

Bradford Public Libraries Committee :
Mr. T. Roles (27 Feb., 1919).

Bristol University :
Mr. H. F. Proctor (8 Jan., 1925).

British Cast Iron Research Association :
Mr. E. B. Wedmore (25 Sept., 1924).

British Electrical and Allied Industries Research Association :
Mr. Ll. B. Atkinson (2 April, 1919).
Mr. F. Gill, O.B.E. (2 Nov., 1922).
Mr. R. T. Smith (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (20 Nov., 1924).
Mr. W. B. Woodhouse (5 Mar., 1925).

Sectional Committee on Electric Control Apparatus Research :
Major H. C. Gunton (2 Feb., 1921).
Mr. W. E. Highfield (19 Mar., 1925).

British Electrical Development Association :
Mr. R. A. Chattock (5 Feb., 1925).
Mr. R. Hardie (18 Jan., 1923).
Mr. W. R. Rawlings (17 Jan., 1924).

Electric Vehicle Committee :
Col. R. E. Crompton, C.B. (22 Oct., 1925).
Mr. W. R. Rawlings (22 Oct., 1925).

Sub-Committee on Constitution :
Capt. J. M. Donaldson (4 Dec., 1924).

British Engineering Standards Association :

Main Committee :
Mr. Ll. B. Atkinson (17 Jan., 1924).
Col. R. E. Crompton, C.B. (17 Jan., 1924).
Mr. C. P. Sparks, C.B.E. (5 Mar., 1925).

Sectional Electrical Committee :
Lt.-Col. K. Edgcumbe (5 Mar., 1925).
Mr. F. Gill, O.B.E. (21 May, 1914).
Mr. J. S. Highfield (21 May, 1914).
Mr. R. T. Smith (21 May, 1914).
Mr. W. B. Woodhouse (19 Dec., 1918).

Sectional Committee on Ball and Roller Bearings :
Mr. W. M. Selvey (26 July, 1921).

Sectional Committee on British Standards in Colonial and Foreign Trade :
The President (*ex-officio*).

Sectional Committee on Colliery Requisites :
Mr. C. T. Allan (3 July, 1924).

Birmingham Regional Committee :
Mr. C. Jones.

Glasgow Regional Committee :
Mr. F. Anslow.

Manchester Regional Committee :
Mr. W. T. Anderson.

Newcastle Regional Committee :
Mr. S. A. Simon.

Sheffield Regional Committee :
Mr. M. Wadeson.

Sub-Committee on Mining Electrical Plant :
Mr. C. P. Sparks, C.B.E. (23 April, 1925).

Sectional Committee on Illumination :
Lt.-Col. K. Edgcumbe (28 Feb., 1924).
Mr. P. Good (28 Feb., 1924).
Mr. H. T. Harrison (28 Feb., 1924).
Prof. J. T. MacGregor-Morris (28 Feb., 1924).
Mr. J. M. G. Trezise (19 Mar., 1925).

Sectional Committee on Petroleum Products :
Mr. H. W. Clothier (1 Feb., 1923).

Sectional Committee on Pipe Flanges :
Mr. W. M. Selvey (14 April, 1921).

Sub-Committee on Electrical Accessories :
Mr. H. J. Cash (31 Mar., 1925).
Mr. F. W. Purse (31 Mar., 1925).

Sub-Committee on Electrical Instruments :

Lt.-Col. K. Edgcumbe (15 Feb., 1923).

Sub-Committee on Electrical Nomenclature and Symbols :

Mr. C. C. Paterson, O.B.E. (8 Jan., 1920).

Sub-Committee on Overhead Transmission Lines Material :

Mr. P. Rosling (5 Mar., 1925).

Sub-Committee on Standardization of Wireless Apparatus and Components :

Mr. E. H. Shaughnessy, O.B.E. (30 Sept., 1925).

Panel on Prime Movers for Electrical Plant :

Mr. F. Bolton (22 Jan., 1925).

Panel on Switches, Ceiling Roses and Wall-plug Sockets :

Mr. H. J. Cash (23 Jan., 1924).
Mr. F. W. Purse (23 Jan., 1924).

Sub-Panel on Graphical Symbols for Interior Installations :

Mr. J. R. Cowie (13 Nov., 1924).

Engineering Joint Council :

Mr. J. S. Highfield (5 Mar., 1925).
Mr. R. T. Smith (5 Mar., 1925).

Imperial College of Science and Technology, Governing Body :

Mr. W. M. Mordey (12 April, 1923).

Imperial Mineral Resources Bureau Conference :

Mr. J. H. Rider (23 Jan., 1919).
Mr. W. B. Woodhouse (23 Jan., 1919).

Copper Committee :

Mr. B. Welbourn (18 Sept., 1919).

Miscellaneous Minerals Committee :

Prof. E. Wilson (18 March, 1920).

Institute of Metals, Corrosion Research Committee :

Mr. W. M. Selvey (19 July, 1923)

Institution of Civil Engineers, Engine and Boiler Testing Committee :

Mr. R. A. Chattock (19 Oct., 1922).
Mr. C. P. Sparks, C.B.E. (19 Oct., 1922).

Institution of Heating and Ventilating Engineers, Committee on Utilization of Exhaust Steam and Waste Heat :

Mr. P. V. Hunter, C.B.E. (29 Sept., 1922).
Mr. W. M. Selvey (29 Sept., 1922).
Mr. J. C. Wigham (29 Sept., 1922).

International Illumination Commission, British National Illumination Committee :

Lt.-Col. K. Edgcumbe (27 Nov., 1913).
Mr. P. Good (18 Sept., 1919).
Mr. H. T. Harrison (27 Nov., 1913).
Prof. J. T. MacGregor-Morris (27 Nov., 1913).
Mr. J. M. G. Trezise (19 Mar., 1925).

International Scientific Unions :

Committee on International Union in Physics :

Dr. A. Russell, F.R.S. (18 Mar., 1920).

Committee on International Union in Radio Telegraphy :

Dr. W. H. Eccles, F.R.S. (18 Mar., 1920).
Prof. G. W. O. Howe, D.Sc.(18 Mar., 1920).
Prof. E. W. Marchant, D.Sc. (18 Mar., 1920).

Leeds Civic Society :

Mr. E. C. Wallis (27 Mar., 1919).

Leeds Municipal Technical Library Committee :

Mr. W. B. Woodhouse (19 Dec., 1918).

Loughborough Technical College, Advisory Committee :

Mr. R. B. Leach (27 Mar., 1919).

Metalliferous Mining (Cornwall) School Governing Body :

Mr. J. S. Highfield (18 Sept., 1919).

Middlesbrough Technical College, Governing Body :

Mr. E. Edwards (1 Oct., 1925).
Mr. J. M. Gibson (1 Oct., 1925.)

National Physical Laboratory, General Board :

Mr. Ll. B. Atkinson (21 Oct., 1920).
Dr. A. Russell, F.R.S. (22 Nov., 1923).

National Register of Electrical Contractors :

Col. R. E. Crompton, C.B. (5 Mar., 1925).
Mr. P. V. Hunter, C.B.E. (12 April, 1923).
Mr. W. R. Rawlings (15 Mar., 1923).
Mr. W. M. Selvey (15 Mar., 1923).

Professional Classes Aid Council :

Sir James Devonshire, K.B.E. (28 April, 1925).

Royal Engineer Board :

Mr. W. B. Woodhouse (19 Mar., 1925).

Royal Society :

Alloys of Iron Research Committee :

Mr. J. Swinburne, F.R.S. (15 Feb., 1923).

National Committee for Physics :

Dr. A. Russell, F.R.S. (16 Dec., 1920).

National Committee on Radio-Telegraphy :

Dr. W. H. Eccles, F.R.S. (4 Aug., 1920).
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DIELECTRIC PROBLEMS IN HIGH-VOLTAGE CABLES.

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SUMMARY.

The paper deals with several important problems of particular theoretical and practical interest at the present time in connection with the design, manufacture, and operation of high-voltage impregnated-paper cables.

In the first place, the phenomenon of dielectric absorption is discussed as a question of fundamental importance and as a basis for a proper understanding of dielectric losses. It is shown how dielectric resistance must be carefully defined in order to be of any value as a characteristic of cable quality, or in analytical discussion, and the results of experiments are given to show that whilst the usually accepted absorption expression departs from the truth, it can be used within limits. Experimental work on absorption in different dielectrics and on the effect of moisture and temperature on the constants is also described.

The dependence of alternating dielectric losses on direct-current characteristics is discussed, and the author suggests a conception of the former in which they can be explained as I^2R losses, without retaining the difficulties of a dielectric hysteresis.

Several new points are brought to light and supported by experimental evidence in a discussion of the relationship between d.c. and a.c. losses. The nature of the " V " curve connecting dielectric power-factor and temperature is investigated, and an explanation of the " V " curve is suggested based on the I^2R theory of losses.

The paper also discusses the rise of power factor with voltage, the important effect of time on the breakdown strength, and the bearing which this has on the effect of surges in a system. In conclusion, some suggestions are made on the nature of breakdown and the assessment of cable quality.

CONTENTS.

(I) INTRODUCTION.

There are many questions affecting the design, manufacture and operation of high-voltage cables which are of considerable interest at the present time, and the scarcity of communications to the Institution on the subject is a sufficient justification for the present paper, if only because of the opportunity which it will afford for the discussion of some of these questions.

The author found in attempting to arrange the paper that the selection of material presented a very real difficulty. There is so much of what may be called " half knowledge " that one is liable on the one hand to take for granted much that is doubtful, or, on the other hand, to restate partially-accepted fundamentals and so risk the charge of being unoriginal.

The paper is intended neither as an exact exposition of any part of the subject nor as a complete summary of all published knowledge. The author feels that in a subject like dielectrics any conception which makes the ideas more tangible to the general body of electrical engineers is of as much value as, if not more value than, a rigid mathematical treatment. He has been content, therefore, to bring together certain items from widely divergent sources, some of which were conceived without any thought of their connection with high-voltage cables, and to add some of the results of six years of his own personal investigations in the hope that the *mélange* so produced may add to our common stock of knowledge of this most important factor in modern electrical engineering.

With all that has been done and written the field of dielectric theory is so widely unexplored to-day that any communication, such as the present one, must necessarily expose many gaps in our knowledge. If at these points, however, the better appreciation of our present ignorance, either through the paper or through the discussion thereon, should also show the way to some probable explanation, a good purpose will have been served.

The three dielectric characteristics most generally considered in high-voltage cable work are :—

Alternating-current losses ;
Alternating-current breakdown strength ;
Dielectric resistance (measured by direct current).

The order of importance is a matter of opinion, and the connection between the three is not at all understood. The third item was considered to be of prime importance for many years, whilst to-day the one receiving most attention in connection with high-voltage cables is that of a.c. losses. In the following pages attention is called to the claims of breakdown strength when measured in a particular manner, which might almost be considered to be a test of a fourth characteristic, the ability to withstand operating conditions satisfactorily over long periods of time ; and the shortcomings of loss and power-factor tests are emphasized.

For some time there has been a growing conviction

that the phenomena displayed under the conditions employed for measuring the d.c. resistance are at the bottom of a.c. losses. For this reason, and as the view seems reasonable, prominence has been given in the paper to the consideration of dielectric absorption, on the lines of the valuable conceptions of Maxwell,* Hopkinson,† Pellat ‡ and Schweidler,§ whose contributions on the operation of dielectrics are generally unknown to electrical engineers.

The correlation between a.c. and d.c. phenomena has been hindered in the past by the fact that d.c. resistance has usually been measured at voltages of 500 or less, whilst a.c. loss measurements have been carried out at very much higher voltages—10 000 and upwards—and the uncertainty of the effect of voltage has made it impossible to bridge the gap between the two sets of published results. The former difficulties of carrying out d.c. tests at the higher voltages have now largely disappeared, through the recent advances in the design of mechanical and thermionic rectifiers, but in the author's experiments the subject has been approached from the other point of view, viz. that of retaining the low voltage for the d.c. tests and developing methods of dielectric-loss measurements for the same low voltage. Alternating-current tests carried out under these conditions admittedly do not bring to light the phenomena connected with the ionization of air entrapped in the dielectric, as met with in super-tension cable work; but the investigation and discussion of this factor separately are an advantage rather than otherwise in throwing light on the operation of the dielectric. In any case, the bringing together of a.c. and d.c. data for the same dielectric seems to be imperative for the fuller understanding of the complicated phenomena encountered. It does not take us the whole way, but it enables us, for example, to obtain a new conception of dielectric losses independent of that much-worn word "hysteresis." By the theory here put forward alternating dielectric losses are explained as I^2R loss, caused simply by a current flowing through a resistance as in other types of electrical loss, and the idea of dielectric hysteresis becomes unnecessary.

Apart, too, from theoretical considerations, the d.c. phenomena in cable dielectrics are assuming importance in connection with the proposals to transmit large quantities of power by high-tension direct current, as well as by the use of unidirectional pressure-tests on high-voltage a.c. cable systems. The connection between alternating and steady potential characteristics may be considered from many different points of view, some of which are discussed in this paper.

Recent experience on high-voltage cables has demonstrated the need for improved tests which, while not damaging the cable, will enable a purchaser to discriminate between a cable that will fail within a few months under ordinary conditions of service and one that will stand up satisfactorily in operation over a long period. The question of assessment of cable quality has, consequently, been given attention, following on the more fundamental considerations. The question of the mechanism of breakdown in cables has received a good deal of attention by many investigators, but is by no means fully understood. The author has ventured to add still one more to the alternative suggestions already advanced.

* See Appendix II, (6). † *Ibid.*, (7). ‡ *Ibid.*, (8). § *Ibid.*, (9).

Owing to the intricacies of the subject, confirmation of any theory of dielectric operation is difficult. The allocation of insufficient weight to the evidence of any one particular phenomenon may result in conclusions entirely opposed to the truth, so that long and detailed research with much hard thinking will be necessary before all the problems now presenting themselves are solved with certainty. In these circumstances, any original views advanced in this paper are put forward tentatively and with a full appreciation of the possibility of the conclusions being negatived by further experimental evidence.

In view of the many excellent bibliographies recently compiled on the subject of cable dielectrics, it has not been considered necessary to attempt a complete list in this instance, but a list of contributions actually referred to in the paper has been given in Appendix II.

(II) Dielectric Absorption (Theoretical).

For more than half a century the various phenomena exhibited by a dielectric when subjected to a steady difference of potential have been studied by many investigators. As long ago as 1861 some very interesting observations were made on the subject by expert witnesses before a Royal Commission on Submarine Telegraph Cables,* and in 1873 Professor Boltzmann † by means of experiments on the attraction between suspended balls of various dielectrics showed how the apparent specific inductive capacity varied with the duration of charge. The phenomenon of "electrification" has long been known in connection with the testing of gutta-percha cables, and it has recently appeared in a new form in connection with the testing of a.c. power cables with high-pressure direct current generated either by the Delon apparatus or by rectifying valves.‡ If a cable for a working pressure of, say, 33 000 volts be charged up to 100 000 volts for a few minutes and afterwards short-circuited, it is not safe to remove the short-circuit for some time, as the residual charge absorbed by the cable will leak back and charge the conductor to a dangerous value.

For two distinct reasons the study of dielectric absorption is important in connection with high-voltage cables. In the first place it is becoming increasingly evident that a.c. dielectric losses are largely the result of this d.c. absorption; and secondly, the demands for the consideration of the claims of direct current for high-voltage long-distance transmission are becoming more and more insistent. For both reasons a summary of the underlying principles of absorption are called for in a paper of this kind.

When a dielectric is subjected to a steady difference of potential there is at first a rush of current, which gradually dies away in the manner indicated in Fig. 1, ultimately approaching asymptotically a steady finite value which, with high-class dielectrics, appears to be extremely small. The time during which the current continues to fall may be weeks, and possibly longer.

* See Appendix II, (1). † *Ibid.*, (2).
‡ *Ibid.*, (3, 4 and 5).

If we consider the quantity of electricity stored in an absorptive condenser, we find that a certain charge is taken immediately on the application of the difference of potential, and a further charge continues to accumulate at a decreasing rate as shown diagrammatically in Fig. 2. The ordinate RS represents the charge acquired suddenly, and the total charge at the time t is the sum of RS and QS, where QS is the charge "absorbed" up to time t. After infinite time the total charge is given by PR.

On discharging an absorptive condenser which has been charged for some time, the discharge current falls away from an initially high value in the same way as the charging current (Fig. 1). The quantity of electricity

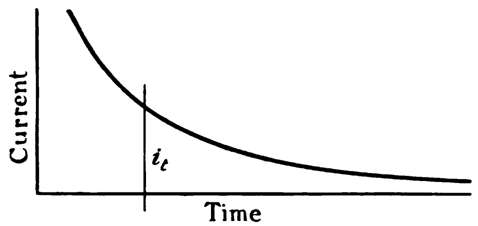

FIG. 1.—Charging current in an absorptive condenser

stored decreases as shown in Fig. 3, first suddenly by a given quantity RS and then more and more gradually. The ordinate PQ of the curve ST at any time after the instant of short-circuit represents the charge still held, or absorbed, by the dielectric and known as the residual charge. If the short-circuit is removed soon after the initial discharge the residual charge, in leaking out of the dielectric, may build up the potential difference of the plates of the condenser to a value approaching that of the original charge.

Consideration of the three elementary diagrams of Figs. 1, 2 and 3 illustrates one or two points which are

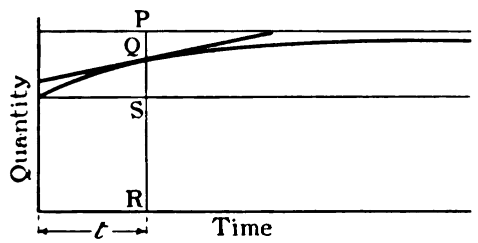

FIG. 2.—Variation of charge with time during charging.

not always appreciated in connection with the meaning of dielectric resistance and capacity. It is common practice in the commercial testing of electric cables to define the dielectric resistance as the ratio between the applied voltage and the current which is flowing 1 minute after the application of the testing battery. As will be seen, this must be an entirely arbitrary value and by no means a true resistance. As a means of arriving at any scientific understanding of the dielectric the 1-minute resistance is useless. The result 2 minutes after the application of the battery will be very much higher than the 1-minute value, and a cable which has quite a low 1-minute value may, after being charged for 24 hours, give a value of dielectric resistance approaching infinity as considered on the usual standards.

As regards the capacity measured by a ballistic galvanometer on charge or discharge, it will be seen that the measured value has two components :—

(*a*) That based on the instantaneous charge or discharge RS (Figs. 2 and 3) ;
(*b*) That based on the charge absorbed or released subsequently on discharge (SQ, Figs. 2 and 3).

(*a*) is known as the geometric capacity and (*b*) as the absorptive capacity.

The relative proportion of the two components included in the value given by the ballistic galvanometer depends on the period during which the galvanometer is connected ; the shorter this time the nearer will the value be to the true or geometric capacity.

Two main theories claim to explain in different ways the mechanism of dielectric absorption and residual charge. The first one, advanced originally by Maxwell,*

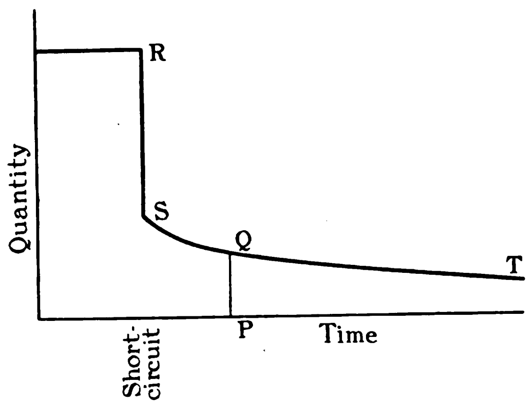

FIG. 3.—Variation of charge held during discharge.

depends on the distribution of charge throughout a non-homogeneous dielectric. He considered the component capacities and resistances in the dielectric and showed that the distribution of potential under transient conditions is settled largely by the arrangement of component capacities, whereas that under steady conditions is fixed by the arrangement of component resistances. The time-lags of electrification and de-electrification are considered in this theory to be due to the time occupied in the rearrangement of potential between one of these conditions and the other.

In the second theory advanced originally by Hopkinson † and since elaborated by other writers, the phenomena are connected with the movement of the electron in the atom. Dielectric polarization is assumed to have two components, a perfectly elastic one accounting for the geometric capacity and a viscous one resulting in absorption. The rearrangement of the electrons during polarization is supposed to take place in two stages : first a sudden jump on the application of the difference of potential, and secondly a steady creeping up to a higher value.

In addition to the development of physical conceptions of the operation of dielectrics, a good deal of

* See Appendix II, (6). † *Ibid.*, (7).

work has been carried out along the lines of mathematical analysis originating with the classical contribution of Pellat,* followed by that of Schweidler † and others.

The adoption of Maxwell's original idea of a heterogeneous dielectric seems to be most useful for cable work, and by the use of this conception it is possible to build up a very simple theory which at the same time conforms exactly to the deductions of Pellat and Schweidler. The theory has, moreover, the advantage that it can be used not only for explaining dielectric absorption under d.c. conditions, but also as a basis for a simple conception of dielectric losses under a.c. conditions.

Various arrangements of pure condensers and resistances have been proposed to imitate a practical dielectric (see, for instance, Fleming and Dyke ‡ and MacLeod §). If we take two condensers and resistances connected as in Fig. 4 we can obtain an approximation to a practical absorptive condenser. The one condition to be met is that the ratio of the capacities must be different from the inverse ratio of the resistances, that is :—

$$\frac{R_A}{R_B} \neq \frac{C_B}{C_A} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It is evident that under steady conditions the potential of the centre point of the combination is settled by the ratio of the resistances, the capacities having no effect. Under transient conditions, however, such as occur at the instant of applying a difference of potential across the group, the potential of the centre point is controlled by the ratio of the capacities, and the resistances have relatively no effect. The potential distribution will be as shown in Table 1, where E is the applied E.M.F.

TABLE 1.

Condition	Potential difference across A	Potential difference across B
Steady	$\dfrac{R_A}{R_A + R_B}E$	$\dfrac{R_B}{R_A + R_B}E$
Transient	$\dfrac{C_B}{C_A + C_B}E$	$\dfrac{C_A}{C_A + C_B}E$

At the instant of switching on, therefore, such an arrangement acts as a pure capacity taking a heavy momentary charging current. Immediately, also, the redistribution of potential described above commences and requires further current, which dies away until, when steady conditions are attained, only that flowing through the resistances remains. Thus all the requirements of an absorptive condenser during charge are met.

In the same way the phenomena of residual charge are imitated on discharging. When short-circuited, a sudden rush results in the total discharge of the smaller condenser and the taking from the other of an equal quantity. At this instant a quantity of electricity equal to the difference between the full charges of the two component condensers is set free and commences to discharge partly through its bridging resistance and partly through the other resistance component and the external circuit, the latter part representing the residual charge. If, after the initial short-circuit, the external circuit is opened, the discharge of the larger condenser which is still in progress charges the outside plates, giving rise to another phenomenon noted with absorptive condensers—the repeated reappearance of a charge on the plates after temporary short-circuits. It is evident, then, that such an arrangement of condensers and resistances, in addition to giving all the charging characteristics of an absorptive condenser, also imitates the conditions during discharge. Exact expressions for the rate of charging of such a combination can be obtained from very simple considerations in order to form a basis for discussing the various phenomena encountered.

If i is the instantaneous current flowing into a condenser of capacity C after time t through a resistance R due to a steady E.M.F. E, then the various quantities are connected by the expression :—

$$E = Ri + \frac{Q}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where Q is the charge in the condenser after time t and

$$E = Ri + \frac{1}{C}\int_0^t idt \quad . \quad . \quad . \quad . \quad . \quad (3)$$

the solution of which gives

$$i = \frac{E}{R}e^{-t/(CR)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and $$Q = EC(1 - e^{-t/CR}) \quad . \quad . \quad . \quad . \quad (5)$$

Now let us apply this to the charging of the combination shown in Fig. 4. Assume that $C_B > C_A$ and

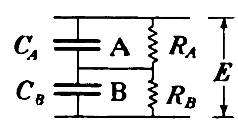

FIG. 4.—Simple arrangement of condensers and resistances to illustrate absorption effects.

$R_A = R_B$.* and that the applied E.M.F. is maintained at the value E.

There are three component currents to be considered:—

α, the initial rush of current which charges the two condensers in series by equal amounts ;

β, the current which flows directly through R_A and R_B ;

γ, the current which flows through R_A to supply the additional charge required by C_B the larger condenser in order to adjust the potential across A and B equally for ultimate steady conditions.

The charges carried by items α and γ are as follows :—

(α) $$Q_1 = \frac{C_A C_B}{C_A + C_B}E$$

This has an instantaneous and definite value.

* See Appendix II, (8). † Ibid., (9). ‡ Ibid., (10). § Ibid., (11).

* This assumption complies with the condition $\frac{R_A}{R_B} \neq \frac{C_B}{C_A}$.

(γ) Applying Equation (5) we get :—

$$Q_2 = E(C_B - C_A)\,[1 - e^{-t/R_A(C_B - C_A)}]$$

Substituting C for $\dfrac{C_A C_B}{C_A + C_B}$

ϵC for $(C_B - C_A)$

and α for $\dfrac{1}{(C_B - C_A)R_A}$

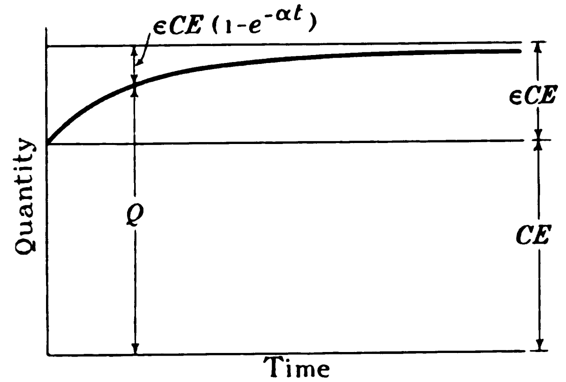

FIG. 5.—Variation of charge, illustrating Equation (6).

we find that the charge stored in the combination t secs. after the E.M.F. was applied is the sum of α and γ and is given by

$$Q = CE + \epsilon CE\,(1 - e^{-at}) \quad . \quad . \quad . \quad (6)$$

This equation is equivalent to that obtained in Pellat's classical and fundamental analysis, and is shown graphically in Fig. 5.

Suppose now that instead of taking only two condensers and two resistances, we consider an infinitely large number of them as shown in Fig. 6. As before

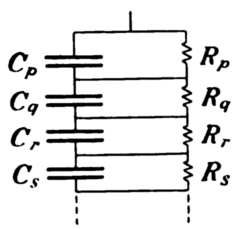

FIG. 6.—Model dielectric to illustrate absorption.

we will assume the resistances to be equal and the capacities to increase downwards. Then we shall have an infinite number of circuits between the upper plate of the condenser and the lower one. These circuits will be made up as follows :—

Circuit No. 1.—C_p, C_q, C_r, C_s . . .
Circuit No. 2.—R_p, C_q, C_r, C_s . . .
Circuit No. 3.—R_p, R_q, C_r, C_s . . .
etc.

Circuit No. 1 is a pure capacity and the remaining circuits form a series with different time-constants. Extending the argument used above in connection with the two condensers, we now obtain for the total quantity of electricity stored up to time t the following expression :—

$$Q = CE + CE\int \epsilon\,(1 - e^{-at})dt \quad . \quad . \quad (7)$$

and this is equivalent to the expression obtained by Schweidler as representing more nearly the operation of an absorptive condenser than did the original expression of Pellat.* At the instant of closing the circuit the charge CE enters the condenser. Immediately also an infinite number of additional charges commence to increase from zero at different rates, as indicated by the collection of curves in Fig. 7. The dotted line represents the sum of these component curves and approaches asymptotically the ordinate $CE\,(1 + \epsilon)$.

The charging current flowing into the combined circuit of Fig. 6 can be obtained either by differentiating the expressions already deduced for the charge or, better still, by the application of Equation (4). One of the elementary currents is given by

$$i_t = \frac{E}{R}e^{-t/(CR)}$$
$$= \frac{E}{R}e^{-at}$$

From the same considerations as those which led to Equation (7) for the charge we obtain the following

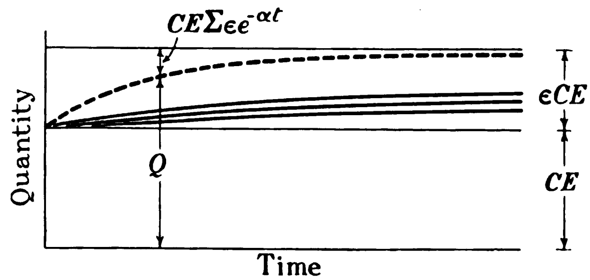

FIG. 7.—Effect of different time constants of component circuits in model dielectric.

expression for the total current flowing after time t through the series of circuits with various time-constants :—

$$I_t = \frac{E}{R}\int_{a=0}^{a=\infty} e^{-at}dt \quad . \quad . \quad . \quad . \quad . \quad (8)$$

It is obvious that this analysis does not lead to a formula which can be employed for the practical estimation of the current flowing in an absorptive condenser after a given period, so that for this purpose we are compelled to fall back on an empirical expression. The form of the charging-current/time characteristic has been studied by various investigators and several different expressions to approximate to the results of tests have been published. Trouton and Russ † gave the formula

$$I_t = \frac{A}{t + B}$$

* See Appendix II, (8 and 9). † *Ibid.*, (12).

where t is the time,
I_t is the current flowing, and
A and B are empirical constants.

Malcolm * found that for one gutta-percha cable

$$I = A + B/\sqrt{t}$$

but that this expression was not satisfied by results obtained on another cable.

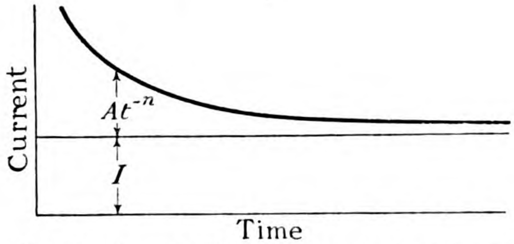

FIG. 8.—Usual empirical charging curve for absorptive condenser.

The most commonly used expression, which has been adopted within recent years by, for instance, Ashton,† MacLeod,‡ and Granier,§ is as follows :—

$$I_t = I + At^{-n} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where I is a true conduction current still flowing after infinite time. A and n are constants, the latter having a value less than unity, and the quantity At^{-n} represents the current supplying the absorbed charge (see Fig. 8).

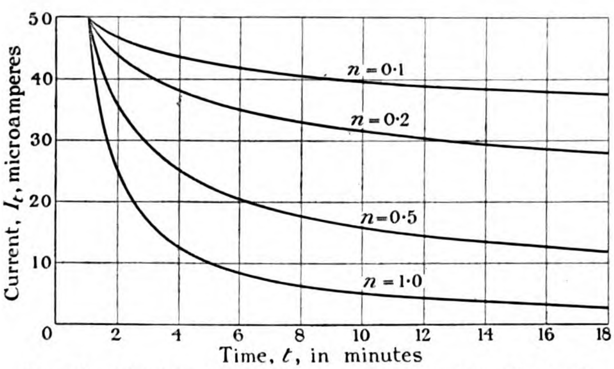

FIG. 9.—Empirical absorption curve, showing effect of varying n.

It will be shown later by examination of results already published, as well as by the author's own experiments, that this expression never does represent accurately the actual variation of current in a cable dielectric over any considerable period of time. It appears to be sufficiently accurate over short intervals (seconds) to make it useful in connecting the d.c. and a.c. characteristics of a dielectric, and if we adopt the convenient reservation that n itself varies with time, we can use the expression in the form given with considerable advantage both for analytical discussion and for the interpretation of practical results. Fig. 9 shows the relative shapes of current/time curves calculated for different values of n from $0 \cdot 1$ to $1 \cdot 0$ and, to anticipate for a moment, curves plotted from experimental results obtained on cables appear to start on one value of n and to change gradually with time to a different value. It is at once evident from Fig. 9 that the 1-minute value is an imperfect indication of the nature of the dielectric. A number of cables may all have the same 1-minute value and yet have widely different characteristics depending on the value of n.

Two methods of determining the values of the constant from an experimental curve are worked out in Appendix I allowing for the presence of I in the formula $I_t = I + At^{-n}$. In passing, it may be noted that in view of the change of n with time which is found to take place in all cable dielectrics so far examined, the determination of the constants from different finite parts of the curve may lead to different values of I, in some cases the early portion giving a negative value, as shown in Fig. 10.

To sum up the theoretical considerations at this stage it is evident that whether we are discussing the correct

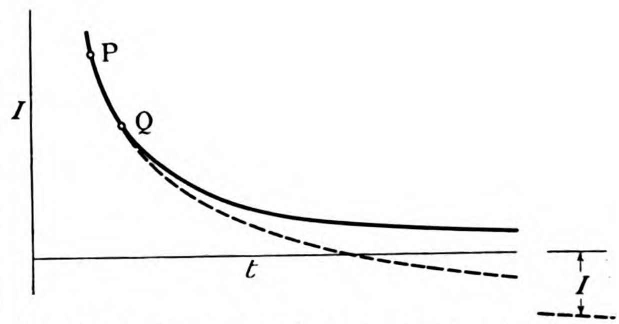

FIG. 10.—Empirical absorption curve, showing change of I.

ratio to adopt between d.c. and a.c. pressures for high-voltage testing, comparing d.c. and a.c. losses for theoretical interest, attempting to show that a.c. losses are partly due to d.c. resistance, or any other of the similar problems that are receiving special attention to-day in connection with high-voltage cables, we cannot be too precise in our definition of the d.c. resistance. Although the whole phenomenon of absorption can be shown as above to be based on resistance within the dielectric, the value of this resistance is elusive. If there is such a quantity as a true dielectric resistance, it is reasonable to take the final value based on the current after infinite time, and this is difficult to determine experimentally. The 1-minute value usually accepted in cable tests, although quite an arbitrary quantity, is as useful for practical purposes as any other that can be suggested at the present time from theoretical considerations, but a more complete knowledge of the dielectric may be obtained by taking into account not only the value at 1 minute, but also the ultimate value and the rate at which the value varies with time, in other words the values of I and n in the tentative expression $I_t = I + At^{-n}$.

* See Appendix II, (33). † *Ibid.*, (13). ‡ *Ibid.*, (11). § *Ibid.*, (14).

(III) Dielectric Absorption (Experimental).

Several investigators have experimented with a view to determining absorption data on different dielectrics, but when examined in detail the results so far obtained on cables do not form a very useful supplement to the theory as outlined in the previous section. Fundamental problems which at once suggest themselves are the following :—

(1) The determination of I and n in the expression $I_t = I + At^{-n}$.
(2) The effect of temperature change on these quantities.
(3) The effect of moisture content.

In attacking this apparently simple programme very considerable difficulties are encountered. The determination of the charging-current/time curve is fairly straightforward, but the deduction of the values of I and n from it is not so easy. In Appendix I two methods adopted for the determination of these quantities from a series of charging currents are indicated. In the first the results are plotted to a large scale and the value of n is deduced from the ratios of tangents drawn to the curve. Method (*b*) arrives at the result arithmetically by the use of three points on the curve. Method (*a*) is less cumbrous than (*b*), but suffers from the disadvantage that errors in drawing the tangents have a large effect on the accuracy of the results. A method of curve analysis given in a recent German book * promises more accurate results by the use of a development in spherical harmonics, but the methods shown have been sufficient for the purposes of this paper.

The results of a large number of experiments carried out by the author show that n may change considerably between, say, 15 seconds and 5 minutes, and, in addition, the final value of I to which the curve is approaching may be different at different times. In a curve, for instance, which ultimately approaches zero the application of the empirical absorption formula to the early part of the curve may lead to a negative value for I, as already shown in Fig. 10. The methods of Appendix I enable the values of these quantities to be obtained nothwithstanding these vagaries. For comparison of different dielectrics, or for checking the effect of moisture or temperature, it is not necessary to consider this change of n with time, but the value can be calculated over the whole period as though it were constant. The approximation is sufficient to show the phenomena under consideration.

The most important dielectric to consider for high-voltage cables is, of course, impregnated paper, but as gutta-percha has been studied from the point of view of absorption for so many years in connection with telegraph cables, and as the empirical formula referred to at the end of the previous Section has been derived from these results, it is of interest first of all to look briefly at the charging-current curve obtained on a cable insulated with this material. Fig. 11 shows the curve obtained by plotting the currents recently given for a gutta-percha cable by Beauvais and shown in Table 2.

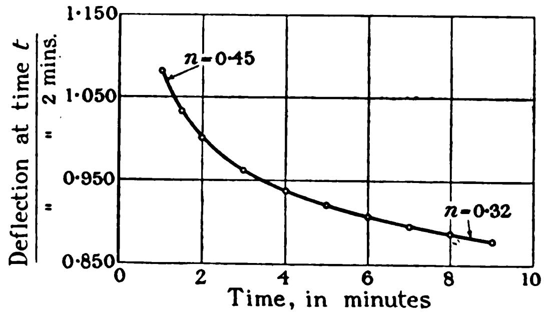

Fig. 11.—Charging current of a gutta-percha cable

Plotting these results on a large scale, measuring tangents and deducing n by the first method of Appendix I, gives $n = 0·45$ at 1 minute, falling to $0·32$ at 9 minutes. Different values of I and A are obtained for the two points, and the limits of the curve may be represented by the expressions

Table 2.

Time	1	1½	2	3	4	5	6	7	8	9
Deflection at time t / Deflection at 2 mins.	1·081	1·031	1	0·961	0·937	0·920	0·906	0·896	0·887	0·879

$$I_t = 0·8 + 0·281t^{-0·45} \text{ (at 1 minute)}$$
$$I_t = 0·49 + 0·397t^{-0·32} \text{ (at 9 minutes)}$$

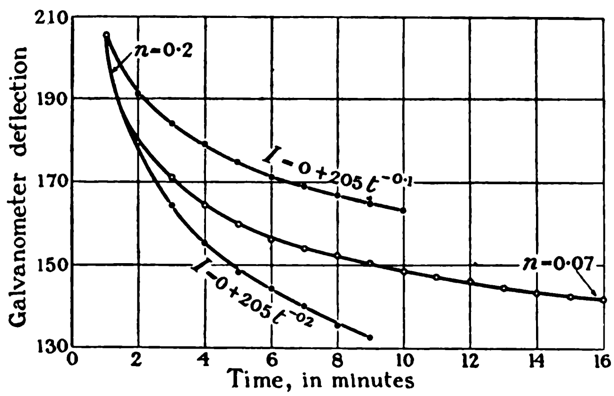

Fig. 12.—Charging current of a gutta-percha cable.

Fig. 12 shows a set of figures obtained on another gutta-percha cable from 1 to 16 minutes, in which the calculated index falls from 0·2 to 0·07. The curves

* See Appendix II, (34).

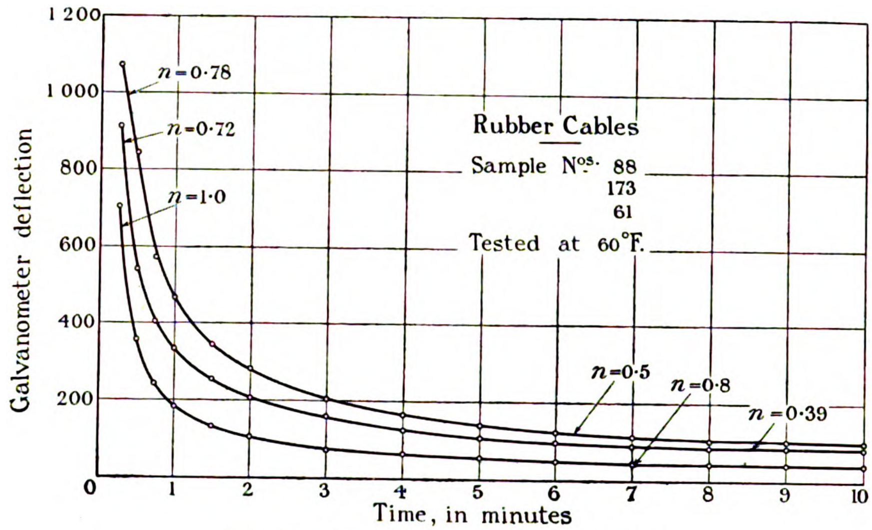

FIG. 13.—Charging current of rubber cables.

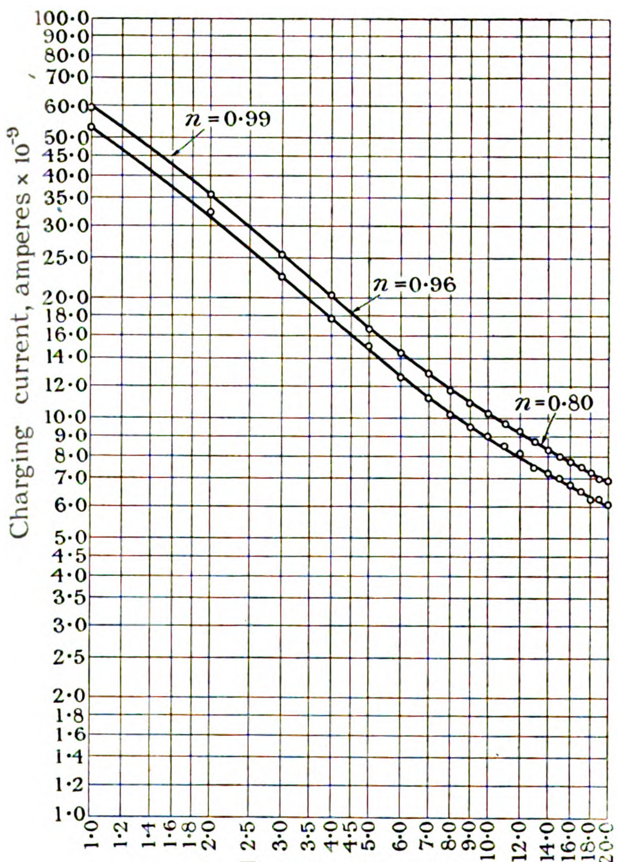

FIG. 14.—Charging current of single-core paper cable.

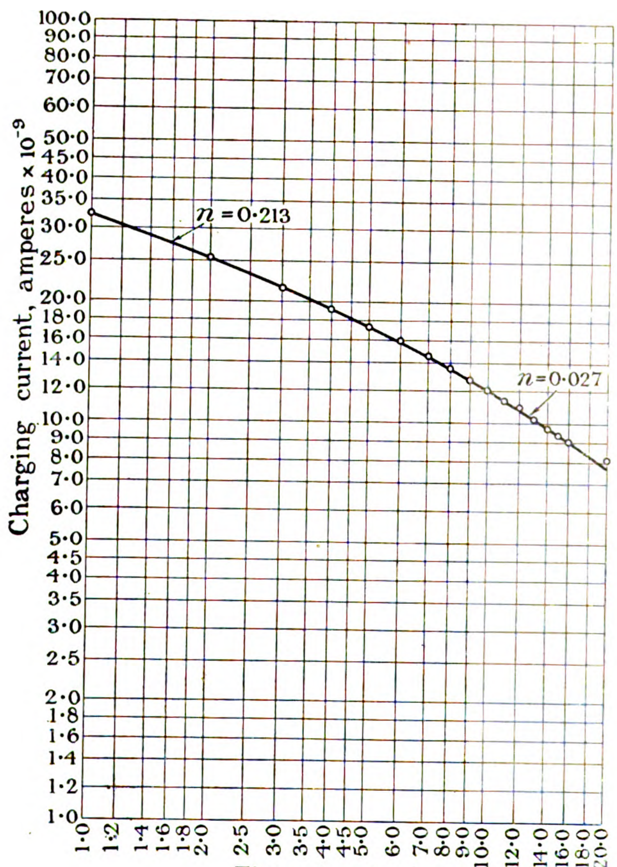

FIG. 15.—Charging current of single-core paper cable, showing effect of change in the empirical constant *I*.

$I = 0 + 205t^{-0\cdot 1}$ and $I = 0 + 205t^{-0\cdot 2}$ are plotted for comparison.

The three curves in Fig. 13 show the results obtained on three samples of 7/·064 vulcanized-rubber cables having different percentages of rubber. The voltage used was 500 and the samples were at laboratory temperature. Here again it will be seen that the value of the index n falls away during the charging. It is interesting to note in passing that the cable with the highest percentage of rubber had the highest value of n throughout.

Quite a large number of tests have been carried out on various types of impregnated-paper cables, and a selection is made below to illustrate the general results obtained. In Fig. 14 the d.c. charging currents obtained with a pressure of 100 volts on two similar 50-yard lengths of single-core super-tension cable are plotted logarithmically. The values of the index n determined for one of the lengths by the second method of Appendix I are indicated. The value approaches unity for short times, and falls to lower values as the time period is lengthened.

Fig. 15 brings out an interesting point noticed in many of the tests. Plotting the results logarithmically may give a drooping curve while the actual value of the index as calculated is falling. The explanation, of course, lies in the variation of the value of I, the assumed constant in the expression $I_t = I + At^{-n}$. The droop due to change in I more than compensates for the rise due to change in n. If n is constant with zero value of I the graph is a straight line, and with a positive value of I the graph is everywhere concave upwards.

Fig. 16 shows the charging currents obtained on three samples of oil at 40° C. The samples were mixtures of two ingredients used in the manufacture of cables in the following percentages :—

Compound	Ingredients	
	P	Q
	per cent	per cent
A	100	0
B	90	10
C	80	20

They were tested between a brass-disc electrode suspended 1 mm above the flat bottom of a brass container. Statements have been made to the effect that liquid dielectrics show no absorption, although Hopkinson and Wilson in 1897 * gave some figures to show that castor oil did exhibit the phenomenon. The curves of Fig. 16 show that without doubt these compounds are absorptive in their liquid state. The calculated values of the absorption index are also given, and it is interesting to note that although the dielectric resistances of the three oils at any instant during the test are not a direct function of their composition, the values of n are. The index increases rapidly with the addition of ingredient Q.

In order to investigate the effect of moisture content on dielectric absorption it is, of course, necessary to choose a dielectric in which the moisture content can be conveniently controlled during the tests. Paper was at first tried, but was abandoned because of its very great susceptibility to rapid atmospheric change. Other materials were tried, but the selection ultimately fell on celluloid as being homogeneous, subject to humidity conditions and yet changing so slowly as to make handling during the tests practicable. A number of sheets 9 in. square and 0·062 in. thick were placed in closed biscuit boxes containing beakers of sulphuric acid, the strengths of which were adjusted to give a definite

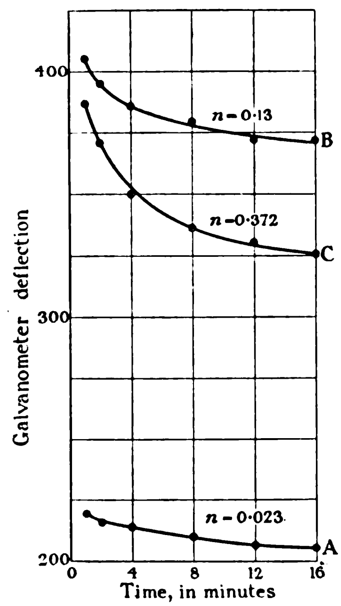

FIG. 16.—Charging current of 3 samples of cable compound.

range of relative humidity of the enclosed air. No. 1 sample had a beaker of phosphorus pentoxide in order that perfect dryness might be simulated as near as possible. The range of humidities covered and strengths of acids used are shown in Table 3

TABLE 3.

Sample No.	Sp. gr. of H_2SO_4	Relative humidity
		per cent
1	(P_2O_5 used)	0
2	1·608	5
3	1·550	10
4	1·510	15
5	1·475	20
6	1·448	25

In order to check the progress of the conditioning of the samples a small piece of the same material weighing about 3 grammes, kept with each main sample in the controlled atmosphere, was taken out and weighed at intervals of 1 week. The weights of the samples steadily changed until after 10 weeks they had settled down sufficiently for the tests to be commenced. Throughout

* See Appendix II, (35).

the tests, which occupied a further 4 months, the samples were kept in the conditioning chambers except during the actual tests, and the strengths of the controlling acids were carefully maintained.

At the time the tests were started, check samples were weighed and put away in a desiccator where they remained until the end of the investigation. They were then re-weighed and it was found as a result that sample No. 1 had continued to lose weight during the investigation. This is an important observation in view of the results, as it shows that the "dry" sample was not perfectly dry.

Care was taken throughout this part of the research to allow a considerable period of time to elapse between any two tests on the same sample, as it was soon dis-

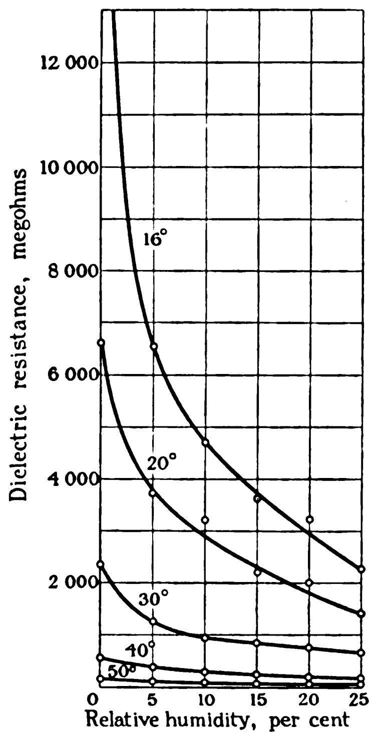

FIG. 17.—Variation of dielectric resistance of conditioned celluloid (82 days' state) with relative humidity and temperature.

covered that the effects of absorption persisted for a surprisingly long time after a test. As a general practice a period of 2 weeks was allowed, and in no case was this reduced to less than 1 week.

In a typical series of tests the samples were inserted in turn between mercury electrodes and the current was measured at the end of 2 hours with a 100-volt battery applied. This test was repeated at 5 different temperatures and the ultimate value of dielectric resistance determined. The curves in Fig. 17 show the definite connection between the dielectric resistance and the relative humidity of the atmosphere under which the samples were stored. In Fig. 18 the logarithm of the dielectric resistance of the extreme cases is plotted against temperature (the other cases lie between) and the results indicate that the law connecting dielectric resistance and temperature is the same for all humidities. It is :—

$$R_\theta = R_0 e^{-0\cdot 06\theta}$$

where R_θ = resistance at θ° C., R_0 = resistance at 0° C., and θ = temperature, °C.

In another set of tests samples 1, 2 and 3 were tested at intervals of 1 minute for an hour and the constants

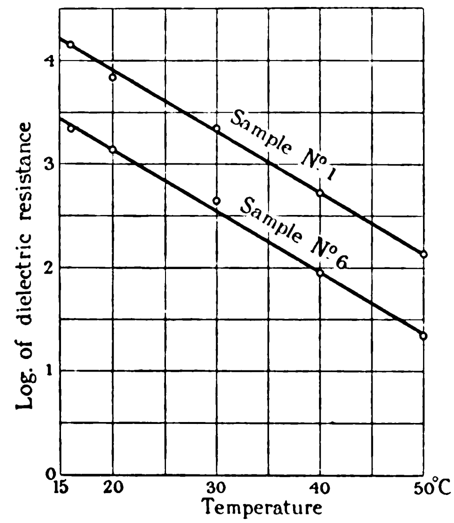

FIG. 18.—Variation of dielectric resistance of conditioned celluloid (82 days' state) with temperature.

in the absorption expression determined. The laws so deduced were as follows :—

Sample No. 1 (dry)

$$I_t = 45\cdot 45 + 14\cdot 55t^{-0\cdot 97}$$

Sample No. 2 (5 per cent relative humidity)

$$I_t = 80\cdot 58 + 24\cdot 82t^{-0\cdot 85}$$

Sample No. 3 (10 per cent relative humidity)

$$I_t = 123\cdot 46 + 27\cdot 54t^{-0\cdot 74}$$

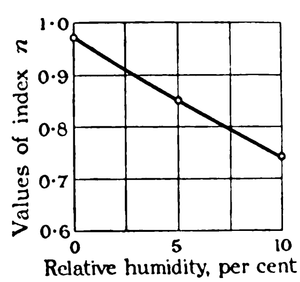

FIG. 19.—Conditioned celluloid (110 days' state). Variation with relative humidity of n in formula $I_t = I + At^{-n}$.

The variation of the index n with the relative humidity of the controlling atmosphere is shown in Fig. 19. It is evident from these results that the presence of moisture lowers the value of n, and it seems probable from the values obtained that if No. 1 sample had been perfectly dried its index would have been unity.

As an example of the effect of temperature on the absorption constants, results obtained on a 30-yard length of 0·1 sq. in. single-core impregnated-paper cable

with 0·1 in. thickness of dielectric will be given. At each of four temperatures from 17° C. to 55° C. a steady pressure of 156 volts was applied for 2 hours and the current/time curves were obtained. From an analysis of these curves the following expressions were obtained for the currents :—

$$I_t = 0\cdot00891 + 0\cdot046t^{-0\cdot885} \text{ (at 17° C.)}$$
$$I_t = 0\cdot0475 + 0\cdot0805t^{-0\cdot645} \text{ (at 29·5° C.)}$$
$$I_t = 0\cdot230 + 0\cdot170t^{-0\cdot508} \text{ (at 41·1° C.)}$$
$$I_t = 1\cdot037 + 0\cdot663t^{-0\cdot341} \text{ (at 55° C.)}$$

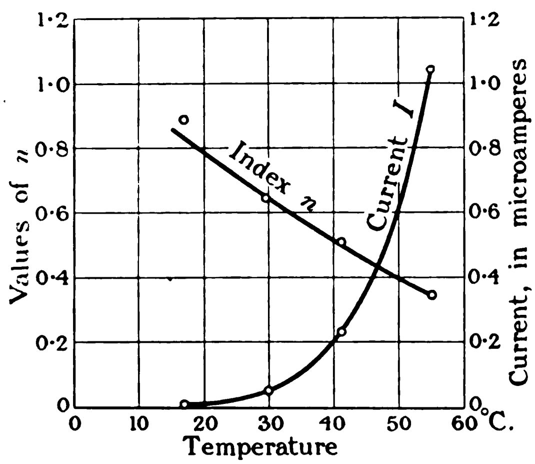

FIG. 20.—Impregnated-paper cable. Variation with temperature of factors n and I in equation $I_t = I + At^{-n}$.

where I_t is the current in microamperes t minutes after the application of the testing voltage.

The values of n and I are plotted in Fig. 20, from which it will be seen that raising the temperature of a paper cable reduces the value of the absorption index.

(IV) FUNDAMENTALS OF A.C. LOSSES.

In Section II the flow of current into an absorptive condenser under a steady unidirectional E.M.F. was considered. Let us now consider what happens when such a condenser is connected to an alternating-current supply. Referring back to the diagram of Fig. 7 and to the d.c. argument, it is evident again that the magnitude of the alternating current flowing will depend on three separate quantities :—

α, the current charging the geometric capacity. This will be a pure wattless current and comparable with that component of the d.c. ballistic capacity current associated with the charge $C E$ (Fig. 7).

β, the current flowing through the dielectric entirely by conduction or leakage.

γ, the current into the capacity associated with absorption or the slow charging of component condensers through resistances.

The component α will be directly proportional to the frequency, and β will be independent of the frequency. The higher the frequency the less will be the charge taken in per cycle under γ, and it is at once evident that the geometric capacity is that calculated from the charging current at infinite frequency. Of the three components of the alternating charging current only β and γ give rise to loss, the first to conduction loss and the second to what is usually styled hysteresis loss (see, for instance, such recent contributions as those of Granier,* Höchstädter,† Frigon,‡ Bruckmann § and Wagner ‖). This idea of hysteresis based on a viscous molecular movement seems to the author to be quite unnecessary for explaining a.c. dielectric losses, and the following outline of an alternative conception, styled for convenience the I^2R theory of dielectric loss, seems to have claims for consideration on the score of simplicity and probability. By this theory, as mentioned in the introduction, dielectric losses are considered to be due to currents flowing through circuits having definite resistances. When an absorptive and leaky condenser

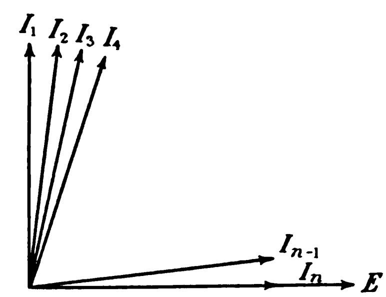

FIG. 21.—Component a.c. vectors in model absorptive dielectric.

is subjected to an alternating E.M.F. the current flowing may be considered to be made up of three distinct components :—

(1) A pure displacement current due to repeated and reversed polarization or elastic displacement of electrons;
(2) An electrolytic conduction from one terminal plate to the other, depending entirely on the movement of free ions;
(3) A combination of (1) and (2) in which elements of distributed or absorbed charge are carried into position by electrolytic conduction.

These three are again associated with α, β and γ above, and as there is complete continuity between them the third assumes supreme importance. It is composed in turn of an infinite number of component currents varying in phase relationship with the E.M.F. from zero to quadrature, as will be clear by referring back to the model of the dielectric in Fig. 6. If the current I_1 flows straight through all the condensers, I_2 first through R_p then through condensers C_q, C_r, C_s, etc., I_3 through R_p, R_q, C_r, C_s, etc., then the vector relationship of the different currents will be as shown in Fig. 21. Each of these imaginary circuits has a distinct power factor ranging from zero with I_1 to unity with I_n (all resistances in series) and in each circuit (apart from the 90° one) energy is dissipated by the flow of current through a resistance. Looked at from this point of

* See Appendix II, (14). † Ibid., (15). ‡ Ibid., (16). § Ibid., (17). ‖ Ibid., (18).

view, it thus becomes evident that a.c. dielectric losses can be considered to be I^2R losses and can be divided into non-cyclical losses, losses due to leakage, and cyclical losses due to absorption. Both presumably have the same origin, but the latter, being due to a current which flows through a condenser in series with the resistance, is thus dependent on the frequency. The value of the resistance in the second case is, of course, experimentally indeterminate.

The above remarks show that a very close connection may exist between the a.c. and d.c. characteristics of a dielectric, and it will be of interest now to investigate the possible interpretation of a.c. dielectric losses in terms of the absorption equation $I_t = I + At^{-n}$ of Section II. In Equation (4) of that Section we have the fundamental expression for the current flowing into a capacity C in series with a resistance R at a time t seconds after the application of an E.M.F. E,

$$i_t = \frac{E}{R}e^{-t/(CR)} = \frac{E}{R}e^{-at}$$

The current flowing into the compound condenser of Fig. 6, representing the absorptive dielectric under d.c. conditions, is then given by a summation of such currents, and Granier has shown * mathematically that the solution leads to a function containing t^{-n}, so connecting up the theoretical considerations with the empirical formula.

If we now consider an alternating E.M.F. applied to our model dielectric and adopt Granier's treatment again, we are led to the following expressions for the in-phase and reactive components of the charging current :—

Energy component $I_w = \frac{1}{2}E_{max.}M\omega^n\Gamma(\frac{1}{2}n)\Gamma(1 - \frac{1}{2}n)$
Reactive component $I_c = \frac{1}{2}E_{max.}M\omega^n\Gamma\frac{1}{2}(1+n)\Gamma\frac{1}{2}(1-n)$

This leads us to a definite expression for the a.c. power factor in terms of the d.c. absorption index n.

For small power factors

$$\cos\phi = \frac{I_w}{I_c} = \frac{\Gamma(\frac{1}{2}n)\Gamma(1 - \frac{1}{2}n)}{\Gamma\frac{1}{2}(1 + n)\Gamma\frac{1}{2}(1 - n)}$$

Values of $\cos\phi$ have been calculated from this expression, and the results are plotted in Fig. 22 to cover a usual range of power factors obtained on impregnated-paper cables. It follows at once from the relationship brought to light in this diagram that, *so far as the losses due to absorption* are concerned, the perfect cable dielectric is that in which the index n in the absorption equation equals unity, giving zero power factor, and the nearer this index approaches its maximum value of unity the lower will be the a.c. power factor. The conclusion also receives considerable support from the experimental results of Section III where the drier and cooler a dielectric the nearer n approaches unity. This is an important conclusion and illustrates the very close connection that does exist between the a.c. and d.c. characteristics of a dielectric. It suggests also a method for the determination of a.c. power factor in which only d.c. tests are applied. The total losses in a given dielectric, however, comprise not only these due to absorption but a further source of loss due to ionization of enclosed air, as will be explained later. The actual power factor determined experimentally will therefore be some value in excess of that given by Fig. 22, by a quantity due to this other cause.

* See Appendix II, (14).

From the above analysis of a.c. conditions it is of interest at this point to make one or two other deductions. The final equation shows that the power factor associated with absorption is independent of frequency, whilst as regards the effect on the losses it follows from the expression for I_w that the energy component and, therefore, the losses due to absorption, are proportional to the nth power of the frequency. In other words, the lower the power factor due to absorption losses the nearer will n be to unity, and the greater will be the dependence of the losses on the frequency. The loss due to direct conduction is, of course, independent of frequency, so that the power factor associated with conduction is inversely proportional to frequency. It follows that in a dielectric having both absorption and

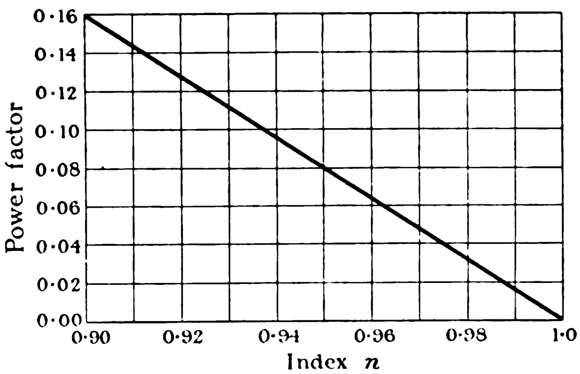

FIG. 22.—Relation between power factor and absorption index (n in equation $I_t = I + At^{-n}$) for losses due to absorption. Calculated from

$$\text{Power factor} = \frac{\Gamma(\frac{1}{2}n)\Gamma(1 - \frac{1}{2}n)}{\Gamma\frac{1}{2}(1 + n)\Gamma\frac{1}{2}(1 - n)}$$

direct leakage the power factor is independent of frequency when the leakage is negligible, and when the leakage predominates over the absorption effect the power factor is inversely proportional to the frequency. Taking 25- and 50-cycle ratios as an illustration, we have

With leakage negligible :

$$\frac{\cos\phi_{25}}{\cos\phi_{50}} = 1$$

With leakage predominating :

$$\frac{\cos\phi_{25}}{\cos\phi_{50}} = 2$$

(V) THE "V" CURVE FOR LOSSES AND POWER FACTOR.

A very important and interesting relationship in the study of cable dielectrics is the variation of dielectric loss with temperature. It has been shown by a number of investigators in America, France, Holland and

Germany during the past few years that over the working temperature-range the dielectric loss in most cables falls to a minimum at about 40°C. and then rises again. The variation when plotted gives rise to what is known as the " V " curve of dielectric loss. The power-factor curve is of the same shape owing to the charging currents being practically unaffected by temperature. So far no satisfactory explanation of the shape of this curve has been given. Clarke and Shanklin,* Proos and others † have attributed the phenomenon to ionization of entrapped gas bubbles. This factor of ionization, which is dealt with more fully later in the paper, does not provide a very satisfactory explanation, and the most promising explanation yet published is that of Höchstädter.‡ He assumes that two types of loss are going on in the dielectric, one a " hysteresis " loss, which definitely falls with rise of temperature, and the other a conduction loss, which has a positive temperature

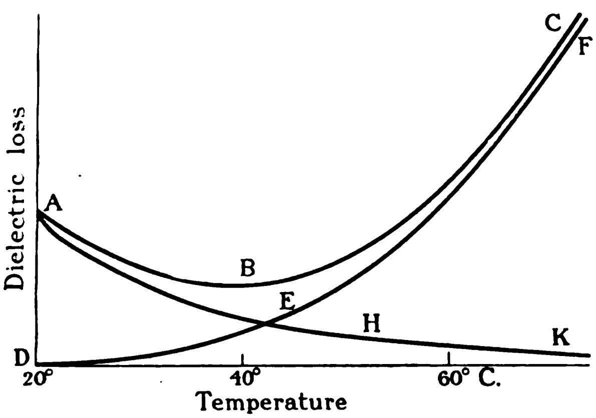

FIG. 23.—The " V " curve resolved into two components.

coefficient. The combination of these two factors produces first a fall and subsequently a rise of the losses as the temperature is increased. Höchstädter takes for granted that the resistance is that obtained by d.c. tests.

The I^2R theory of dielectric losses formulated in an earlier section to replace the hysteresis conception seems to offer a better explanation of the " V " curve. Reverting for a moment to the early part of Section IV, where the component circuits in the model absorptive dielectric of Fig. 6 were considered, we recall that the elementary power factors were in each case proportional to the assumed series resistance. Now this conducting path in a dielectric is of an electrolytic nature with a negative temperature coefficient of resistance. If the temperature be raised the resistance falls and with it the power factor $\cos \phi = \omega CR$. This simple consideration leads at once to an explanation of the " V " curve. Both falling and rising portions are due to change of resistance with temperature. In the former case the resistance is in series with capacity, in the latter it is in parallel. The point is illustrated by Fig. 23, where A B C is the curve obtained experimentally. Curve A H K is the component falling due to the decreasing resistance in series with capacities, and D E F the component attributed to direct leakage.

* See Appendix II, (19). † *Ibid.*, (20). ‡ *Ibid.*, (15).

As the measurement of cable-dielectric power factor is to-day a matter of routine testing, there would be no object in giving here the results of ordinary tests. The

TABLE 4.

Dielectric Loss and Charging Current (frequency = 50 cycles) for 30 yards of 0·1 sq. in. paper cable.

Temperature	Volts	Watts	Amperes
	110	0·00300	0·000915
	100	0·00248	0·000834
	90	0·00201	0·000750
17° C.	80	0·00159	0·000667
	70	0·00122	0·000584
	60	0·00089	0·000500
	50	0·00063	0·000422
	110	0·00258	0·000930
	100	0·00213	0·000847
	90	0·00172	0·000763
29·5° C.	80	0·00136	0·000678
	70	0·00104	0·000594
	60	0·00076	0·000509
	50	0·00053	0·000424
	110	0·00236	0·000882
	100	0·00195	0·000805
	90	0·00159	0·000720
41·1° C.	80	0·00128	0·000644
	70	0·000987	0·000560
	60	0·000773	0·000476
	50	0·000500	0·000396
	110	0·00221	0·00093
	100	0·00170	0·000848
	90	0·00162	0·000760
55° C.	80	0·00115	0·000675
	70	0·00078	0·000592
	60	0·00072	0·000519
	50	0·00044	0·000425
	110	0·00883	0·000874
	100	0·00730	0·000790
	90	0·00600	0·000697
71° C.	80	0·00467	0·000623
	70	0·00360	0·000543
	60	0·00245	0·000450
	50	0·00175	0·000390
	110	0·0219	0·00095
	100	0·0187	0·000868
	90	0·0151	0·000765
85° C.	80	0·0120	0·000684
	70	0·0092	0·000598
	60	0·0068	0·000514
	50	0·0047	0·000428

author has, however, carried out a series of tests embodying one or two unique features illustrating the question of the " V " curve, which may be described with

advantage. In most dielectric-loss tests on cables high voltages are employed and, in order to explore a new field, it was decided to carry out a voltage/temperature range of loss tests at quite low voltages. The limits adopted were 50 to 110 volts, and the temperatures varied from 17° C. to 85° C. The cable selected for the test was a 30-yard length of single-core impregnated-paper lead-covered cable with a 0·1 sq. in. conductor and a thickness of dielectric of 0·11 in. A simple modification of the "null" wattmeter method due to Parry and Owen * was adopted for these tests, a Dolezalek electrometer fitted with an extended head and a Wollaston wire suspension being found to give

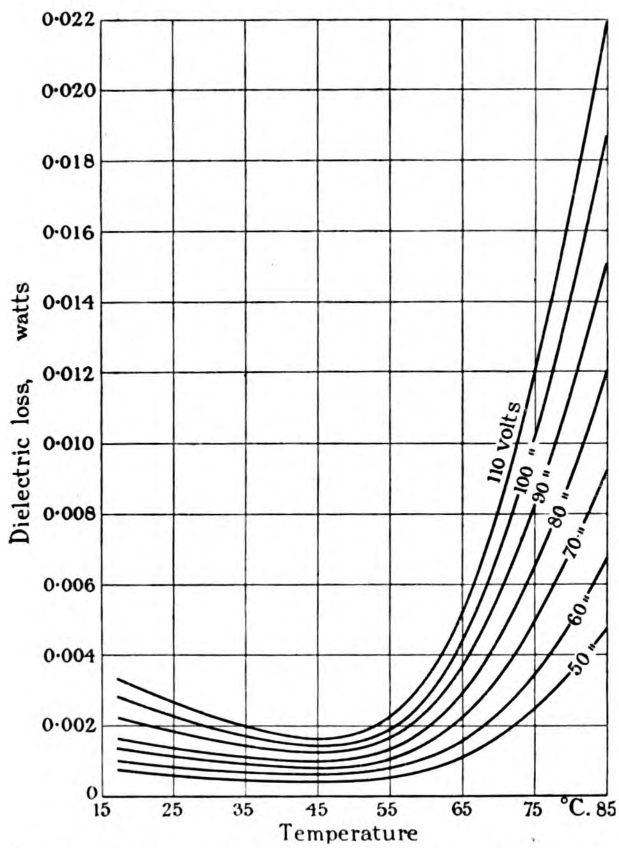

FIG. 24.—Impregnated-paper cable (30 yds., 0·1 sq. in.). Variation of dielectric loss with temperature at low voltages.

the necessary sensitivity for these low-voltage tests. One frequency only, viz. 50 cycles, was adopted and the length of cable was heated by air in an iron tank fitted with circulating fans. The results obtained for loss and charging current are given in Table 4.

In Fig. 24 the dielectric losses are plotted against temperature for the different voltages, and the outstanding feature is the existence of the "V" curve. It is of considerable importance in the explanation of the "V" curve to note that it exists at such low voltages. Fig. 25 gives the power factors plotted from the 110-volt result.

The shape of the "V" curve obtained from power-factor tests on a high-voltage cable may be deliberately

* See Appendix II, (21).

changed by the use of different papers, impregnating compounds, and methods of manufacture. As examples the two curves of Fig. 26 were obtained on two 0·2 sq. in. single-core cables with 0·5 in. thickness of dielectric impregnated with the same compound and manufactured under identical conditions. The only difference between them was that the papers employed for the two lengths were composed of different fibres. Fig. 27 shows the results obtained on another pair of similar cables in which both had the same insulating paper and treatment, but in which different impregnating compounds were employed. The tests recorded in Figs. 26

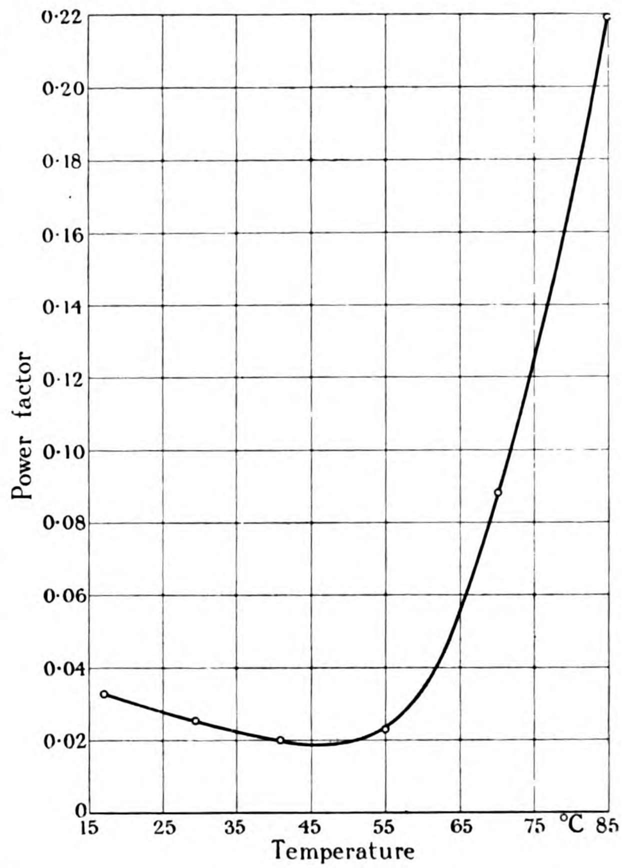

FIG. 25.—Impregnated-paper cable (30-yard length). Variation of power factor with temperature.

and 27 were all carried out at 10 000 volts and 50 cycles. In all cases of impregnated-paper cables, where there is a minimum point in the "V" curve it seems to occur at a temperature about 30° C. to 40° C., but the minimum point can be eliminated entirely by certain treatment. For instance, Fig. 28 shows two curves exhibiting this feature. Cable E was known to be imperfectly dried and the power factor, starting off on an abnormally high value at normal temperature, continues to rise with temperature with no attempt at a minimum point. Cable F was impregnated under special conditions and with a special compound, both of which are known to produce a low power factor. In this case the power factor remains independent of temperature from 20° C. up to 40° C. and then only

rises very slowly. Our present knowledge is insufficient to explain these curious variations in the " V " curve, but they may possibly be based on some peculiarity in the distribution of the elementary currents assumed in our treatment of absorption. If, for instance, the presence of moisture without actually adding direct conduction loads the system of condensers and resistances towards the conductance end of the series, the effect might be to produce a curve like E in Fig. 28. Employing the same mental picture, a curve like F in Fig. 28 could be produced by a " spreading " of the characteristics over the whole of the series. Further reference

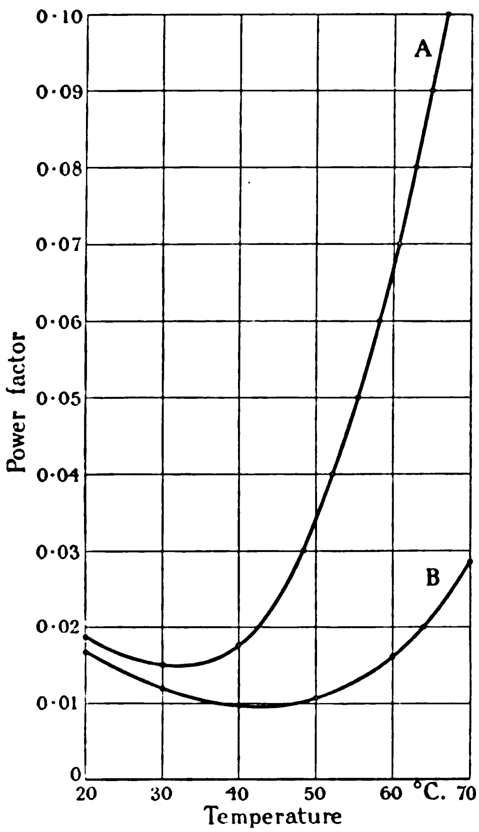

Fig. 26.—Effect of type of paper on power-factor/temperature curve.

is made to this feature in the next Section arising out of the connection between d.c. and a.c. losses.

Considerable light is thrown on the nature of the " V " curve by plotting the results of dielectric-loss tests taken on a length of cable at two different frequencies. Figs. 29 and 30 show the variation of loss and power factor with temperature at 25 and 50 cycles on a length of 33 000-volt cable tested in water over a temperature-range from 50° F. to 150° F. It will be seen that while the 50-cycle loss is approximately double that at 25 cycles at the low temperature, the values run together as the temperature rises and at 150° F. the loss is the same for both frequencies. As the charging current is proportional to the frequency the power-factor curves have the opposite characteristic —they run together at the lower temperature and separate at the higher (see Fig. 30). Considering these curves in the light of the analysis at the end of Section IV, we may be led to deduce that at 50° F. the leakage is negligible and that at 150° F. it predominates,

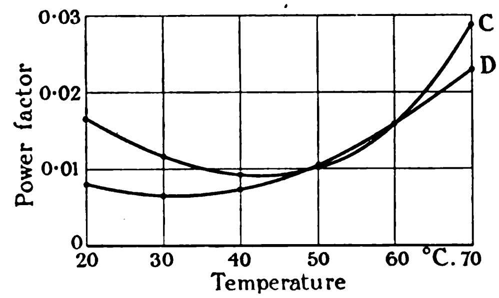

Fig. 27.—Effect of type of compound on power-factor/temperature curve.

but it will be shown in the next Section that this assumption is incorrect. Notwithstanding the fact that the 25- and 50-cycle loss curves run together at the higher temperatures, it does not follow that at this

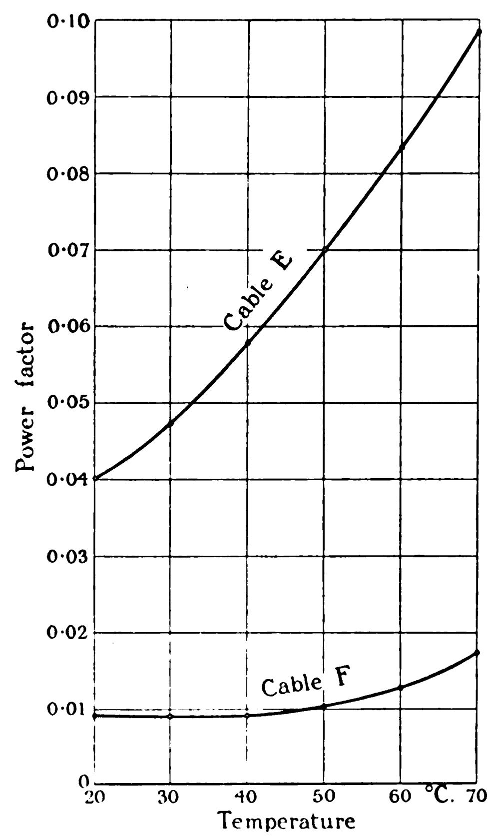

Fig. 28.—Effect of imperfect drying on shape of " V " curve.

temperature the loss is all direct conductance. The evidence is fairly clear that if tests were taken at much lower frequencies than 25, the two curves would separate at 150° F. and for frequencies of the order of

a fraction of 1 per second would separate very widely. The point is further clarified by the experimental results given in the next Section.

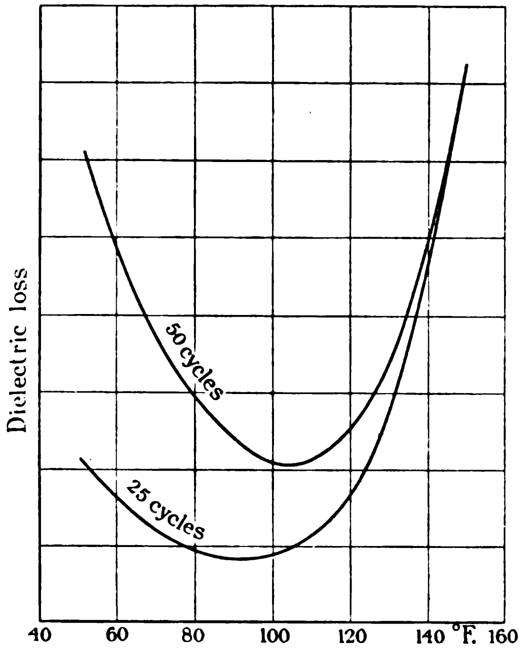

FIG. 29.—Impregnated paper cable. Variation of dielectric loss with frequency and temperature.

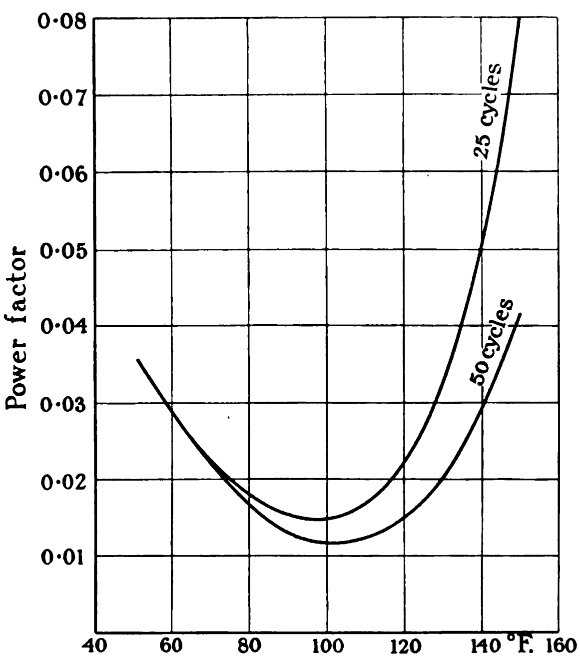

FIG. 30.—Impregnated-paper cable. Variation of power factor with frequency and temperature.

(VI) CONNECTION BETWEEN A.C. AND D.C. LOSSES.

Very little information has been published on the connection between a.c. and d.c. losses in a cable dielectric, but as the question is of considerable interest in connection with the other characteristics under discussion, some steady-current tests have been carried out on the cable referred to in the previous Section (see Table 4) and the connection between the a.c. and d.c. results has been calculated. Check-tests have also been carried out by an entirely different method in order to confirm the important conclusions, but the results from the two sets of tests will be given separately. Addenbrooke has given * a number of ratios of d.c. to a.c. losses on a wide range of dielectrics but only at one temperature, and to broaden the scope of the present tests a temperature range has been

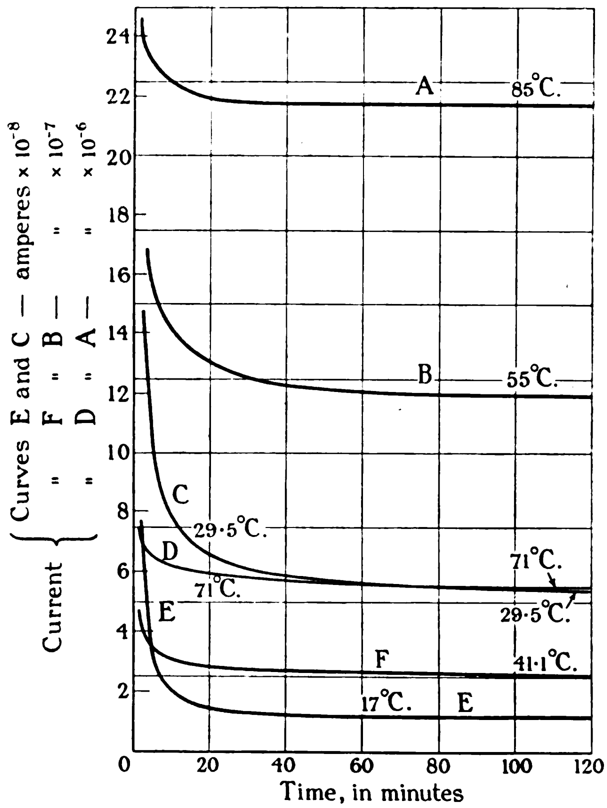

FIG .31.—Impregnated-paper cable (30 yds., 0·1 sq. in., single-core). Variation of d.c. charging current with time.

taken. The steady charging-currents were also recorded at different time-intervals up to 2 hours in the first series and up to 5 minutes in the second, instead of after the attainment of steady conditions as in Addenbrooke's experiments.

Applying d.c. tests to the cable of Table 4 gave the series of current/time curves shown in Fig. 31. Fig. 32 shows the variation of dielectric resistance with temperature for different time-intervals, and Fig. 33 the same plotted logarithmically. Taking the expression

$$R_\theta = R_0 e^{-K\theta}$$

as representing the variation of resistance with temperature, it is interesting to note in passing that the

* See Appendix II, (22).

TABLE 5.

Comparison of A.C. and D.C. Losses in 30-yard length of 0·1 sq. in. single-core Impregnated-Paper Cable, thickness of dielectric 0·11 in.

D.C. Time	17° C. D.C.	17° C. A.C.	17° C.	29·5° C. D.C.	29·5° C. A.C.	29·5° C.	41·1° C. D.C.	41·1° C. A.C.	41·1° C.	55° C. D.C.	55° C. A.C.	55° C.	71° C. D.C.	71° C. A.C.	71° C.	85° C. D.C.	85° C. A.C.	85° C.
	Conductance $\times 10^{-10}$	$\frac{W}{E^2} \times 10^{-7}$	$\frac{A.C.}{D.C.}$	Conductance $\times 10^{-10}$	$\frac{W}{E^2} \times 10^{-7}$	$\frac{A.C.}{D.C.}$	Conductance $\times 10^{-10}$	$\frac{W}{E^2} \times 10^{-7}$	$\frac{A.C.}{D.C.}$	Conductance $\times 10^{-10}$	$\frac{W}{E^2} \times 10^{-7}$	$\frac{A.C.}{D.C.}$	Conductance $\times 10^{-10}$	$\frac{W}{E^2} \times 10^{-7}$	$\frac{A.C.}{D.C.}$	Conductance $\times 10^{-10}$	$\frac{W}{E^2} \times 10^{-7}$	$\frac{A.C.}{D.C.}$
Mins. 2	3·52	2·48	705	8·19	2·13	260	25·6	1·95	76	109	1·7	15·6	500	7·3	14·6	1 520	18·7	12·3
10	1·28	"	1 938	4·86	"	438	19·5	"	100	91·7	"	18·5	436	"	16·7	1 445	"	12·95
60	0·717	"	3 460	3·62	"	588	16·66	"	117	78·5	"	21·6	400	"	18·26	1 396	"	13·4
120	—	"	—	3·39	"	628	16·56	"	118	76·8	"	22·1	346	"	21·1	1 396	"	13·4

Note.—D.C. and A.C. voltages = 100; A.C. frequency = 50.

coefficient K is not the same for all time-intervals, nor is it constant over the temperature range for any one time-interval. At the lower temperature it has a value of 0·045 calculated on the 2-minute readings and 0·055 calculated on the 2-hour readings, whilst in the neighbourhood of 80° C. the values are 0·038 and 0·045 respectively.

Table 5 summarizes the results obtained by comparing the d.c. tests just described and the a.c. tests of the previous Section taken on the same piece of cable.

These results establish several important points. In the first place it is seen that the ratio of a.c. to d.c. losses in a paper cable at low voltages varies between

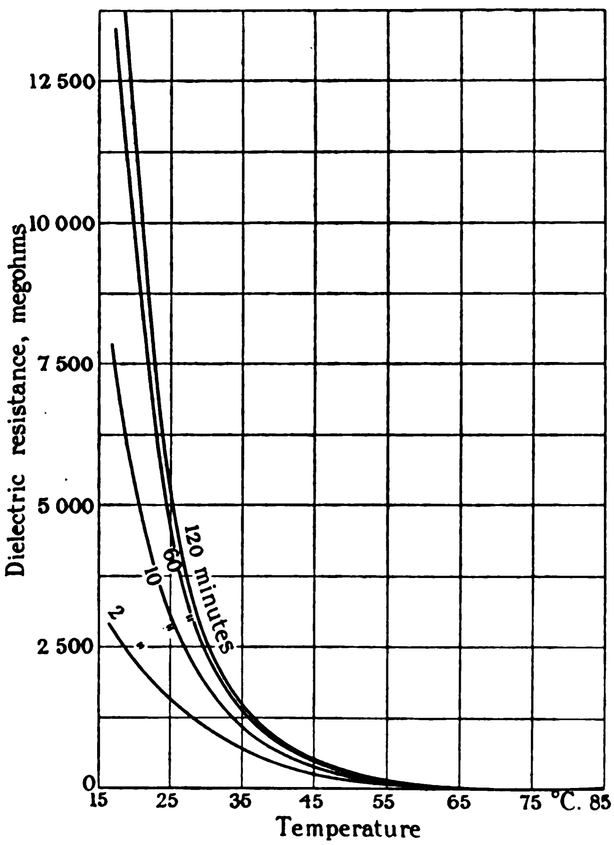

FIG 32.—Impregnated-paper cable. Variation of dielectric resistance with temperature for different time-intervals.

wide limits (in this case from 3 460 to 12·3) depending on the temperature and the time of charging under d.c. conditions. Also the duration of the d.c. charge has a more marked effect on the ratio at low temperatures than at the high ones.

The most important result of all is in connection with the " V " curve explanation advanced in a previous Section. The view sometimes expressed that at the higher working temperatures of paper cables the greater part of the dielectric loss can be attributed to conduction based on d.c. values seems to be wrong. The results obtained in these tests indicate that at 85° C., which is in excess of normal maximum cable temperatures, the a.c. loss is more than 13 times the value calculated on

TABLE 6.

D.C. Tests on 550-yard Length of 0·2 sq. in. Low-Tension Impregnated-Paper Cable.

Temp.	500 volts d.c. Charging currents (microamperes)																			
	15 secs.	30 secs.	45 secs.	60 secs.	75 secs.	90 secs.	105 secs.	120 secs.	135 secs.	150 secs.	165 secs.	180 secs.	195 secs.	210 secs.	225 secs.	240 secs.	255 secs.	270 secs.	285 secs.	300 secs.
° C. 21·5	4·07	3·70	3·42	3·35	3·03	2·82	2·70	2·63	2·29	2·15	1·99	1·93	1·82	1·69	1·60	1·54	1·52	—	—	1·50
50	74·3	49·0	39·7	35·4	32·0	30·1	28·9	27·6	26·7	25·9	25·4	24·8	24·4	23·9	23·5	23·4	23·1	22·8	22·5	22·3
60	132	95·8	84·1	78·1	74·3	70·3	68·8	67·3	66·2	65·8	65·0	64·2	63·8	63·2	62·7	62·3	61·9	61·7	61·6	61·5
70	234	194	178	171	162	160	158	156	155	154	153	152	151	150	149	148	147	146	146	146

the d.c. conductance, even on 120-minute d.c. results. As the conductance was still falling at the end of this time the ratio of a.c. to d.c. loss at 85° C., based on final conductance, must have considerably exceeded the value of 13. The results are plotted in Fig. 34 and show at once that around 80° C. by far the greater part of the 50-cycle losses are cyclical. Following up the argument of Section IV, the difference between the ordinates of the upper and lower curves represents the I^2R losses due to the absorption currents flowing through component resistances, and it seems to follow that the absorption losses have definitely in themselves the two components to produce the dipping curve.

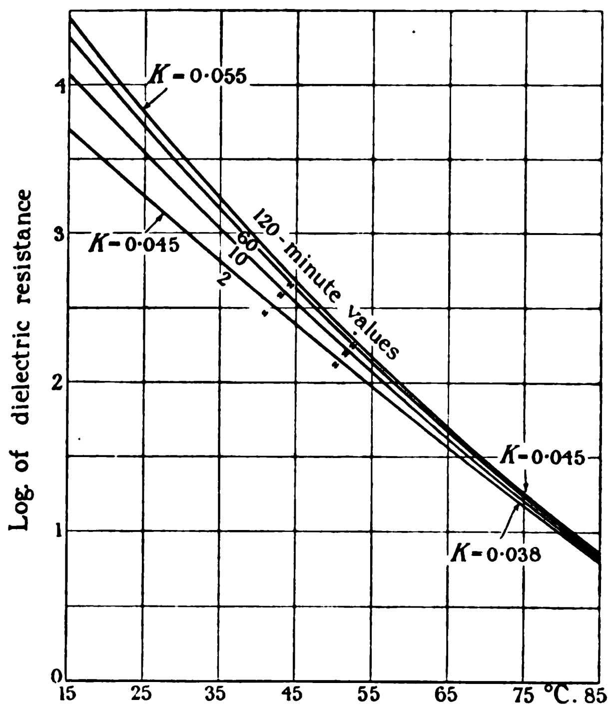

FIG. 33.—Impregnated-paper cable. Effect on the temperature coefficient of resistance of the time-interval adopted

In the second series of tests a length of 550 yards of 0·2 sq. in. low-tension single lead-covered cable was placed in a tank of water heated by steam to different temperatures from 21·5° C. to 70° C. The d.c. charging current from a 500-volt battery was measured at each temperature at 15-second intervals up to 5 minutes and the dielectric loss at 500 volts alternating current (50 cycles) was also measured at the same temperatures by means of a dynamometer wattmeter. The results obtained are given in Tables 6 and 7.

In Fig. 35 the power factor for this cable is plotted against temperature, showing that the results again confirm the fact that the " V " curve exists at these low voltages.

Table 8 gives the ratio of a.c. to d.c. losses for this cable at different temperatures and calculated on different d.c. time-intervals from 15 seconds to 5 minutes. It confirms in a remarkable way the deductions made on the results of similar tests carried out by entirely

different methods and given in the earlier part of the Section—that at any ordinary cable temperature the a.c. losses cannot be approximately attributed to d.c. conduction. At 70° C. the 50-cycle a.c. losses in this cable are more than 24 times the d.c. losses.

TABLE 7.

A.C. Tests (50 cycles) on 550-yard Length of 0·2 sq. in. Low-Tension Impregnated-Paper Cable.

Temperature	Voltage	Per 1 000 yards		Power factor
		Charging current	Loss	
° C.	volts	amp.	watts	
21·5	500	0·122	0·802	0·0132
40	500	0·122	0·365	0·0060
50	500	0·122	0·383	0·0063
60	500	0·122	0·802	0·0131
70	500	0·122	1·77	0·0290

Attempts have been made by some investigators to throw light on the relationship between a.c. and d.c. losses by determining the effect of frequency under the a.c. conditions. Addenbrooke, in the paper already quoted, showed that, except for very low frequencies of the order of 1 or 2 cycles per second, the loss on a large number of different dielectrics was a linear function of the frequency n and that if expressed as

$$\text{Watts} = A + Bn$$

the higher class of dielectrics gave the lower values of A. The author has examined this characteristic for impregnated-paper cables at different temperatures and at two frequencies. A typical set of results is plotted in Fig. 36 for a length of 3-core super-tension cable subjected to 25- and 50-cycle loss tests while immersed in water at various temperatures from 52° F. to 150° F.

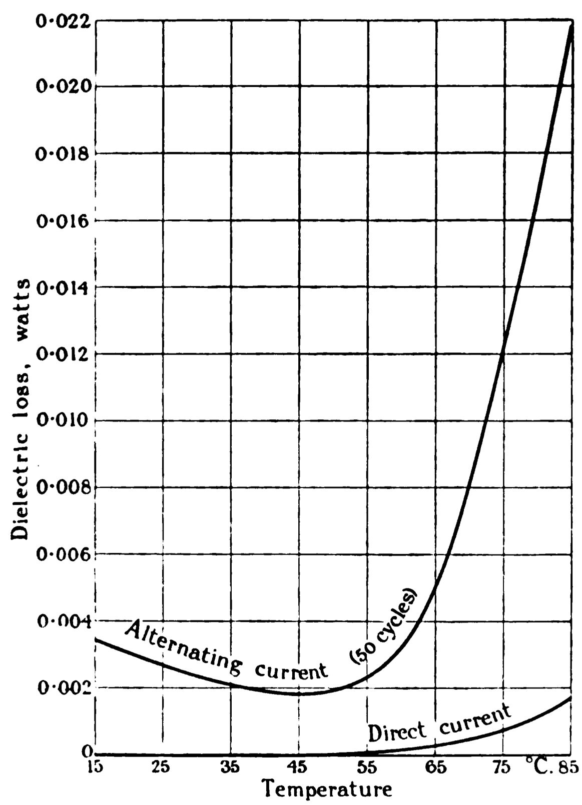

FIG 34.—Impregnated-paper cable. Relation between a.c. and d.c. losses.

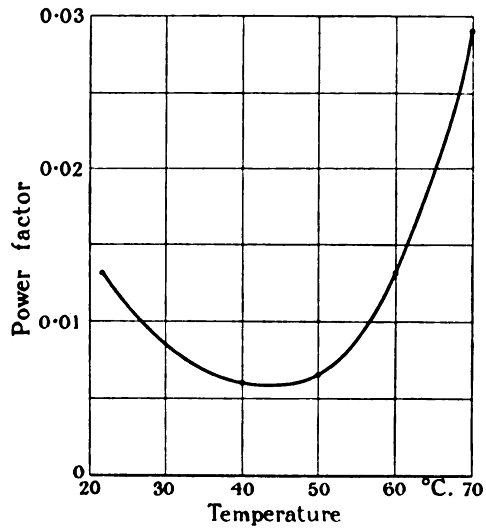

FIG. 35.—Impregnated-paper cable. Relation between low-voltage power factor and temperature.

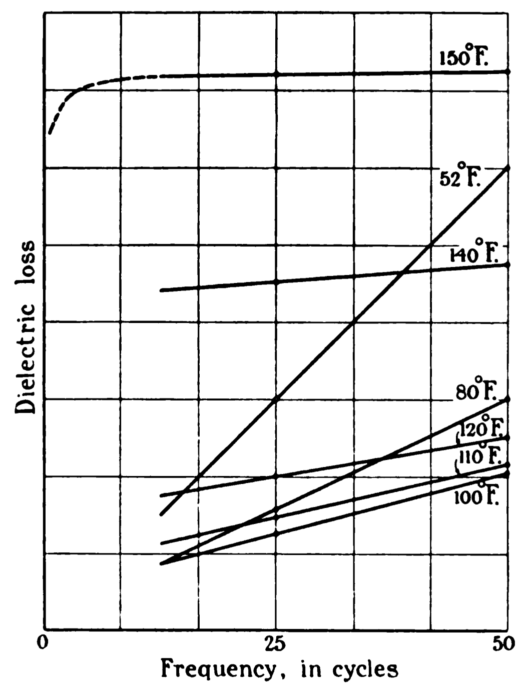

FIG. 36.—Impregnated-paper cable. Variation of dielectric loss with frequency and temperature.

A larger number of frequencies should be taken to make the results more complete, but as they stand the curves show that the characteristic noted by Addenbrooke for different dielectrics is also brought to light by temperature variation in one and the same dielectric. At the low temperature the line connecting 25- and 50-cycle losses passes almost through the origin of co-ordinates, the variation with frequency being high, i.e. A is 0 and B is a maximum. As the temperature rises the slope of the line decreases and the intercept at zero frequency increases, whilst at 150° F. the frequency makes very little difference to the magnitude of the losses. It cannot be assumed, however, from these results that all the loss at 150° F. is "conductance" loss, as is frequently done. The higher-temperature curves in Fig. 36 suggest that at zero frequency, that is, under d.c. conditions, the loss is approximately the same as the a.c. loss, but from the results of actual tests recorded earlier in this Section it is clear that the direct conduction has a very much lower value. The anomaly is is believed to be due to the presence of air entrapped within the cable dielectric. As air has a definite ionizing potential under given pressure conditions it follows that a cable exhibiting ionization at normal voltages should show none at low voltages. Examination of the results of the low-voltage tests given in Section V shows this to be the case. There is no ionization on this cable at 110 volts. The losses for these tests are plotted logarithmically against voltage in Fig. 37, and the results justify very exactly an expression

$$W = PE^m$$

where W = loss in watts,
E = applied voltage, and
P and m are constants. (m is found to be equal to 2 very exactly.)

In other words, the value of W/E^2, sometimes called the a.c. conductance, is constant over the voltage range when measured at a low voltage.

TABLE 8.

D.C. Time	21·5° C.			50° C.			60° C.			70° C.		
	D.C.	A.C.	A.C./D.C.	D.C.	A.C.	A.C./D.C.	D.C.	A.C.	A.C./D.C.	D.C.	A.C.	A.C./D.C.
	Conductance $\times 10^{-9}$	$\frac{W}{E^2}\times 10^{-6}$		Conductance $\times 10^{-9}$	$\frac{W}{E^2}\times 10^{-6}$		Conductance $\times 10^{-9}$	$\frac{W}{E^2}\times 10^{-6}$		Conductance $\times 10^{-9}$	$\frac{W}{E^2}\times 10^{-6}$	
secs.												
15	8·12	3·208	395	149	1·532	10·3	264	3·208	12·1	467	7·08	15·2
30	7·4	,,	433	98	,,	15·6	192	,,	16·7	389	,,	18·2
45	6·85	,,	468	79·3	,,	19·3	169	,,	19·0	356	,,	19·9
60	6·71	,,	478	71	,,	21·6	156	,,	20·6	341	,,	20·8
120	5·26	,,	609	55·2	,,	27·7	135	,,	23·7	313	,,	22·6
180	3·86	,,	830	49·5	,,	30·9	128	,,	25·0	303	,,	23·4
240	3·08	,,	1 040	46·7	,,	32·8	125	,,	25·6	294	,,	24
300	3	,,	1 069	44·7	,,	34·2	123	,,	26·1	293	,,	24·2

Note.—D.C. and A.C. voltages = 500; A.C. frequency = 50.

only apparent, however, and would no doubt be cleared up by loss measurements at frequencies of the order of a fraction of a cycle per second. It is evident that the 150° curve at the low frequencies would fall as shown by the dotted line down to the d.c. value.

(VII) Rise of Power Factor with Voltage.

In addition to the variation of power factor with temperature the effect of voltage is of importance. If the power factor of a dielectric is independent of voltage, then, as

$$\begin{aligned}\text{Watts} &= EI\cos\phi\\ &= E^2\omega C\cos\phi\end{aligned}$$

the dielectric losses are proportional to the square of the voltage. Now this condition is not found to exist in ordinary loss tests on high-voltage cables. The power factor usually rises with voltage, and the losses increase at a greater rate than with the square. This phenomenon is generally known as "ionization" and

In order to examine the probability of the dependence of W/E^2 upon voltage being due to ionization of entrapped air, it is of interest to glance at the phenomena met with in physical experiments on gases, and a series of tests carried out by Mackay * is of considerable interest in this respect. This investigator set up a piece of apparatus in which electrons freed from a nickel target by ultra-violet light were accelerated by means of a variable electric field towards an enclosure containing the gas to be tested. A platinum wire collected the positive ions produced by ionization and the rate of collection was measured by an electrometer and stop-watch. Curves produced connecting the ionizing voltage and the rate of charging of the electrometer were of the general form shown in Fig. 38. That is, below a certain voltage V no ionization of the gas occurred, but beyond that voltage, which was a definite point characteristic of the particular gas, the rate of ionization increased with the voltage. For certain

* See Appendix II, (23).

gases, e.g. oxygen, this investigator showed that there was a second bend in the curve at a higher voltage.

In view of these experiments it is interesting to

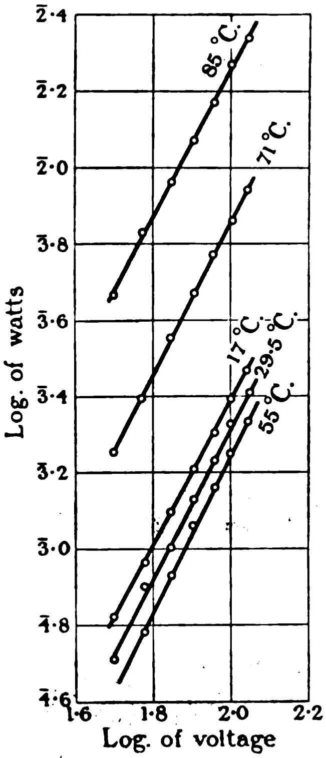

FIG. 37.—Impregnated-paper cable. Variation of losses with voltage at low voltages (50–110 volts, 50 cycles).

examine some of the published results on the ionization of high-voltage cables. Clarke and Shanklin,* and Smit Kleine, Proos and Van Staveren † have investi-

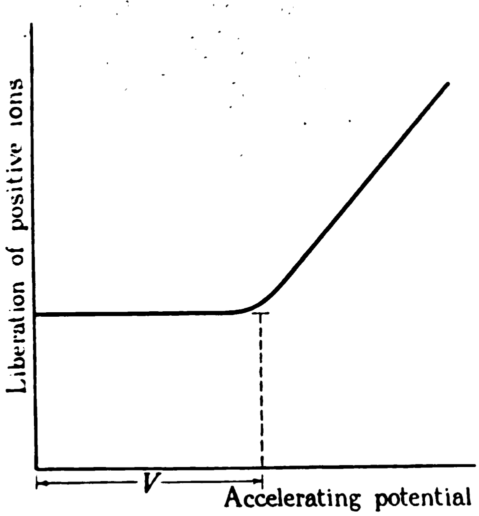

FIG. 38.—Ionizing curve for gas.

gated the question very fully, and have produced curves connecting the power factor of a cable dielectric and the applied voltage which are identical in form with those of Fig. 38. They (particularly the second group of investigators) find that a very sharp cut-off point is exhibited when the power factor or the value of W/E^2, which is the product of the power factor, frequency and capacity, are plotted against voltage. For several reasons the author has always been chary of accepting these results for general application. In the first place, as we have just seen, where a laboratory experiment is set up to determine the ionizing point of a clean uniform gas all at one temperature and pressure, the point of deflection is not sharp owing to all the electrons not having the same energy. In the second place, Dubsky has shown * that the dimensions of an air pocket within a mass of insulating material have a very considerable influence on the ionizing potential. Again, Mackay showed in the experiments just described that different gases had entirely different ionizing potentials. Taking into account these three factors it is difficult to imagine how, in a length of cable, a collection of different pockets of various dimensions, containing different gases and, owing to their different distances from the conductor, subjected

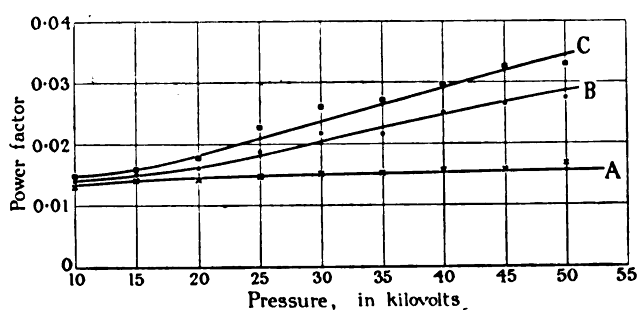

FIG. 39.—Effect of current on power-factor/voltage curve. Single lead-covered 0·2 sq. in. cable.

Curve A.—As manufactured.
Curve B.—After 540 amps. for 4 hours and cooled down.
Curve C.—After 825 amps. for 2 hours and cooled down.

to different ionizing voltages, should all exhibit ionization at one and the same voltage. As a matter of fact, in actual tests on super-tension cables it is unusual to find a sharp bend in the power-factor/voltage curve.

An important factor in any study of the connection between power factor and voltage is the effect of overloading a cable. The tests taken immediately after manufacture may give only a very slight rise of power factor with voltage, but if a heavy current be passed through the cable so as to cause undue heating of the dielectric and expansion of the lead, then the repeat tests carried out on the length after cooling down will give a much sharper rise. This is illustrated by a typical example in Fig. 39, for a 0·2 sq. in. single-conductor lead-covered impregnated-paper cable. After the first series of tests had been taken a current of 540 amperes was passed through the conductor for 4 hours and then the whole cable was allowed to cool to its original temperature and stand for some days, after which the second set of figures was obtained. A current of 825 amperes was then passed through the cable for 2 hours and the loss tests were repeated after

* See Appendix II, (19). † *Ibid.*, (20).

* See Appendix II, (24).

cooling. The third curve shows the results obtained this time.

In view of the dependence of power factor on the

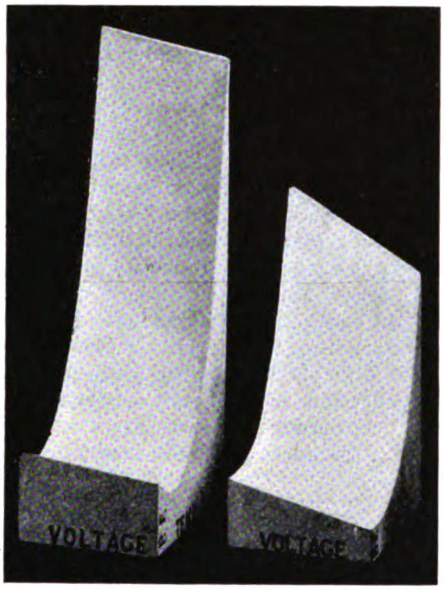

FIG. 40.—Three-dimension diagrams to illustrate the connection between power factor, temperature and voltage. The two curves show the difference brought about by changes in manufacture.

two variables, temperature and voltage, and the need for a quick method of comparing the results on a number of cables, the author has found it convenient to employ solid diagrams for plotting the results. The values of power factor at any one voltage are plotted against temperature, and the curves so formed are cut out of 5-ply wood $\frac{1}{4}$ in. thick. Similar curves are produced for each of the other voltages employed in a series of

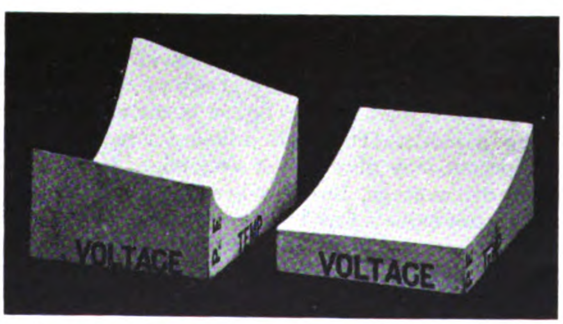

FIG. 41.—Three-dimension diagrams to illustrate the connection between power factor, temperature and voltage. The two curves show the difference brought about by changes in manufacture. These lower values and flatter curves are obtained by the use of special compounds.

tests, and when they are assembled the resulting block gives a very useful bird's-eye view of these particular electrical properties of the cable. In the determination of the effect of modifications in materials or manufacture when carrying out research work on cables, a comparison of two or more such blocks is much easier than the comparison of masses of figures. Figs. 40 and 41 show four sets of results plotted in this way and

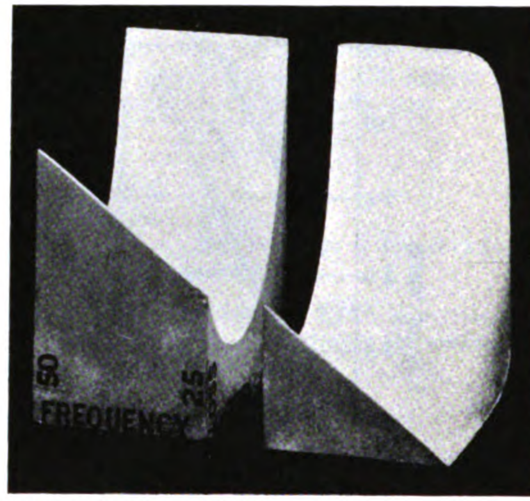

FIG. 42.—Connection between dielectric loss, temperature and frequency from 25 to 50 cycles, with a suggestion for the lower frequencies.

FIG. 43.—Connection between power factor, temperature and frequency from 25 to 50 cycles, with a suggestion for the lower frequencies.

demonstrate the wide variation in shape of the solid power factor-voltage-temperature diagram which may be effected by alterations of materials and processes. The scales of all four diagrams are the same.

The use of similar solid diagrams is also helpful in forming an idea of what happens to the characteristics outside the range actually tested; the left-hand block in Fig. 42, for example, shows a model used to demonstrate the variation of dielectric loss with temperature and frequency, the results being based on 25-cycle and 50-cycle tests. The right-hand block in the same figure shows the probable variation of loss with frequency from 25 cycles downwards to direct-current conditions, and in this connection should be compared with the results illustrated in Fig. 34.

Fig. 43 indicates the manner in which the power factor varies with frequency and temperature, the left-hand block being based on actual test-results, and the right-hand block being a suggestion as to how this quantity varies at the lower frequencies.

(VIII) Breakdown. The Time-Voltage Relationship.

For many years it has been the custom to speak of the breakdown strength of a cable as though it were a definite constant characteristic. We have talked about maximum dielectric stresses of so much—200 kV/cm for instance—and specified that a cable shall withstand such a stress before failure. At the same time anyone who has had experience of cable testing knows that a voltage applied suddenly produces quite different results from one applied slowly, and it has consequently been usual for some time to specify duration pressure tests of 15 or 30 minutes in addition to quick breakdown. It is only quite recently, however, that the exact relationship between breakdown voltage and the time of application to the cable has called for detailed study. One factor leading to the investigation of the matter has been the failure of super-tension cables in operation many months after installation, although they passed the most stringent tests before leaving the factory and on completion of laying. This time effect is quite a new phenomenon and so far very little has been published on the subject. Perhaps the most useful contribution made up to the present time is that by F. M. Clark.* This writer shows that if a fibrous insulating material, such as impregnated paper, be subjected to a succession of voltage applications below the value necessary to cause failure, the dielectric being allowed considerable time for recovery between the applications, its power of resisting a straight breakdown test may be very much impaired. This is a discovery of first-rate importance in the operation of cables. It means that indiscriminate high-pressure tests may seriously affect the life of the cable under working voltage. It also means that a succession of pressure-rises due to surges or lightning on connected open lines, although individually resulting in no failure, may make the cable progressively less able to withstand such voltages.

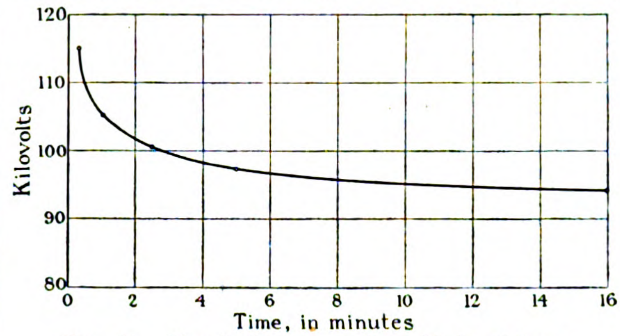

Fig. 44.—Time/voltage curve for cable breakdown.

Developing these ideas the author has made it a practice for some time past to produce time/voltage curves for all cables made under research conditions, with a view to augmenting the information obtained in other tests. The method adopted is to cut up a uniform length of cable into six or eight pieces, each 5 yards long, apply a quick breakdown voltage at a definite rate of increase and then apply 90, 85, 80 per cent, etc., of the value so obtained to the remaining pieces in turn. The time during which the piece holds the

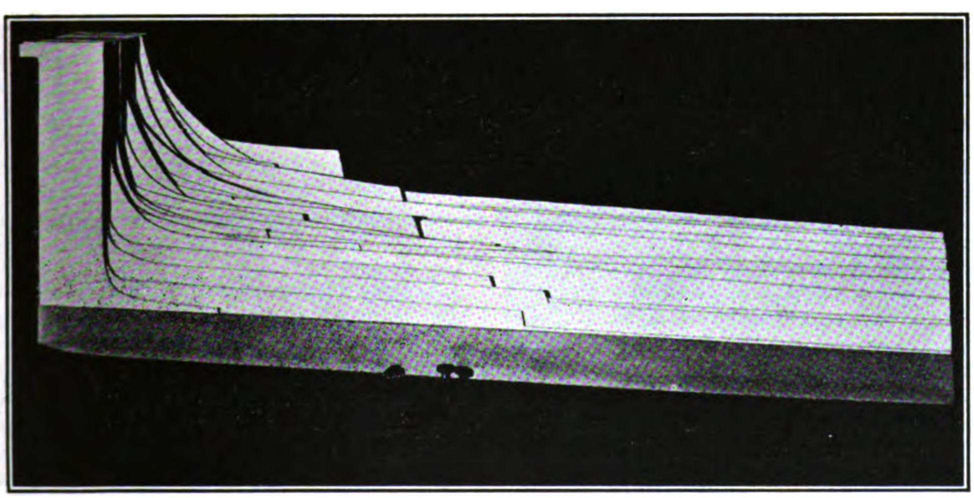

Fig. 45.—Collection of models of time/voltage curves.

* See Appendix II, (25).

voltage is recorded and, as the lower the voltage the longer the time, plotting the results gives a curve as shown in Fig. 44. The slope of the curve is very steep for short times and gradually flattens out until quite a small reduction in the voltage adds enormously to the time that the cable will stand up under it.

Fig. 45 shows a collection of curves produced in this way for experimental cables made up in the investigation of different materials and processes. As an indication of the order of the figures obtained, a good modern 33 000-volt cable will hold 75 000 volts three-phase at normal temperatures for 50 or 60 hours before failure.

It is not clear from these curves whether they ultimately flatten out to a definite voltage or continue to fall at a decreasing rate for ever. By plotting the results in another way, however, we are led to the conclusion that a given cable has a definite voltage below which it would hold up for ever. The method was described by Owen a few months ago.* Instead of plotting the breakdown voltages against time the values are plotted against the inverse fourth root of time. Fig. 46 shows a number of results obtained on single-core and 3-core cables obtained in this way, and it will be seen that the points lie reasonably on straight lines. The greatest merit of the use of this method of plotting seems to be that with it one can deduce with reasonable accuracy the probable voltage that a cable will hold indefinitely. As time progresses from right to left in the diagram the results of tests extending over a few hours only can be used to obtain the straight line which intercepts the axis at the equivalent of infinite time in a definite value of the breakdown voltage for that time. X is the value which would break down the cable if kept on for some centuries, and any value below that would be safe to adopt as a working voltage for the cable in question.

In fairness two weaknesses of the method should be pointed out at once. The safe working voltage so deduced presumes that :—

(1) The sample cut up and broken down is representative of the weakest part of the cable.

(2) The samples are in the same condition as they would be if they had been subjected to the same heating and cooling due to rise and fall of load as would obtain in the practical use of the cable.

Objection No (1) is not very serious—there is little variation between consecutive 5-yard pieces of a well-made cable; but objection No. (2) is not so lightly disposed of. The effect of repeated heating and cooling as shown in connection with the rise of power factor with voltage may also affect the long-time safe voltage. In the present state of our knowledge the best that we can do practically is to determine the point as described and then allow a factor of safety.

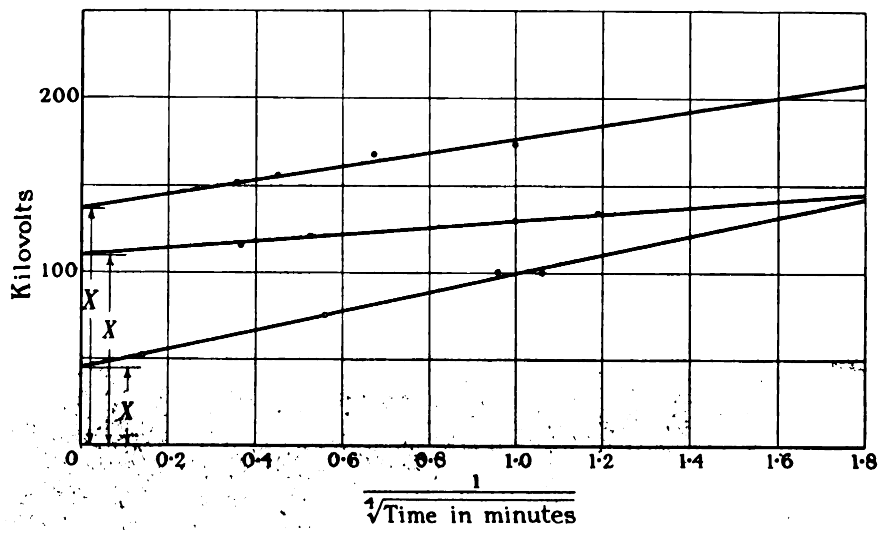

FIG. 46.—Alternative method of plotting time/voltage relationship.

A correct appreciation of this time/voltage relationship leads to an important matter in connection with the operation of large high-voltage cable systems. It is widely appreciated to-day that such systems are liable to obscure pressure-rises in ordinary conditions of service, due to various causes, and that such phenomena are at the root of certain types of cable and transformer failure. As a result there is a tendency to install surge absorbers or protectors, and some very interesting results have already been published in connection with their use. Mr. Partridge, for instance, has shown * that by the installation of a very simple device on a single-phase system working at 10 500 volts to earth he has reduced the number of failures of mains and transformers in a remarkable way. He employs a series of spark-gaps in conjunction with a limiting resistance so arranged as to spark over at 35 per cent over-voltage. He showed by observations over a period of 5 years that the apparatus operated 332 times. If, then, a dielectric may be subjected periodically to these

* See Appendix II, (26).

* See Appendix II, (36).

voltages estimated to rise to several times the working voltage, the results of F. M. Clark quoted at the beginning of this Section, taken in conjunction with considerations of the shape of the time/voltage curve, show that they will have a deteriorating influence greatly in excess of that due to the working voltage. In view of this it is evident that any precautions that can be taken to control the extent of pressure-rises on a cable system are well worth consideration.

(IX) The Nature of Cable Breakdown.

Our views on the nature of cable breakdown are very incomplete. For a long time it has been considered that when the dielectric stress at any point exceeds a certain value that particular part of the material is destroyed as an insulator by molecular disruption. The application of this theory in cable work has led to considerable difficulty. In a concentric condenser such as a single-core cable it leads to the failure being a function of the maximum stress at the conductor, but so far no strong experimental evidence has been advanced in support of this relationship to explain the failure of impregnated-paper cables. In fact quite a reasonable argument has been made by Fernie for attributing failure to the minimum stress at the outer boundary of the dielectric.* An explanation of quite a different kind has been advanced by Wagner † and concurrently by Hayden and Steinmetz.‡ These investigators have attributed the breakdown to a heating of local paths through the insulation, which, having a negative temperature coefficient, may under certain conditions rise to a temperature sufficiently high to cause charring and immediate loss of insulating properties. A weakness of this theory, however, lies in the fact that a certain critical voltage called the "puncture voltage" is assumed to be necessary for puncture, and the existence of the time/voltage relationship covered by the previous Section of this paper is ignored. By the pyro-electric theory, as it is styled, it would only be necessary to allow a cable to cool down after a prolonged high-voltage test and it would be as good as new, but the experiments already described show that this is not so. Without producing breakdown it is definitely established that a high-voltage test may damage the insulation.

As the result of a careful study of the conditions of individual papers taken from different parts of cables both broken down on test and subjected to prolonged pressure test, the author is led to formulate a theory of cable failure differing somewhat from those already advanced. Höchstädter § has discussed failure through tangential stresses, but the true explanation seems to lie somewhere between the tangential-stress theory of Höchstädter and the pyro-electric theory of Wagner.

The detailed examination of cables caught before actual failure in a pressure test reveals the following facts :—

(i) In a single-core cable at any point throughout the dielectric between the conductor and the lead sheath there may be a few consecutive papers showing signs of charring.

* See Appendix II, (27). † *Ibid.*, (28). ‡ *Ibid.*, (29). § *Ibid.*, (30).

(ii) The papers above and below those damaged may be in perfect condition.

(iii) The charred condition is restricted neither to the proximity of the conductor nor to that of the lead. It may occur anywhere in the dielectric.

(iv) In a 3-core cable the same conditions hold, but, generally speaking, the charring occurs mostly on the outer core papers and either along the line of contact between cores or towards the centre of the cable.

(v) In a 3-core cable the belt papers rarely (one hesitates to say never, though this would probably be a correct word) show signs of charring.

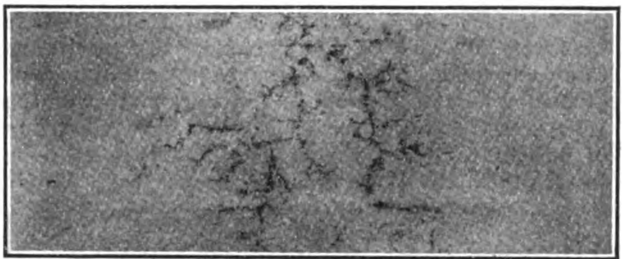

Fig. 47.

The general appearance of this deterioration on papers from a single-core cable is shown in Figs. 47 and 48, the second one showing the action in a more advanced state. Figs. 49 and 50 show two stages in the progress of this deterioration in the papers from a 3-core cable, and similar examples have been given by the author elsewhere.*

In the earlier part of this paper it was contended

Fig. 48.

that all a.c. dielectric losses are I^2R losses, the cyclical ones being due to the dissipation of energy when a current charging a condenser flows through a resistance. Now no cable dielectric is perfectly homogeneous, and to fix our views let us consider what goes on in a single-core cable. If the dielectric were perfect and uniform the lines of current-flow would be radial throughout and the current would be a pure displacement current. In a practical cable, however, we have two important departures from ideal conditions. We have :—

(*a*) A layered dielectric where each layer contains paper fibres which no doubt have tiny quantities of moisture and so form electrolytic conducting paths perpendicular to the theoretical direction of the electric field.

* See Appendix II, (31).

(b) Inequalities in the contact between layers which result in a difference of impedance between one radial path and another.

Fig. 51 shows the result that may be expected from such considerations. Suppose that at point P there is a small patch where the two layers of paper are not making

FIG. 49.

as efficient contact with one another as they do elsewhere. This weakness may be due to slackness of the papers, to an impervious spot in the paper preventing passage of the impregnating compound, or to imperfect drying. Whatever the cause, the result is to deflect the lines of flow of the displacement current and in so doing to turn them out of the radial direction. Immediately,

FIG. 50.

the power factor of this part of the dielectric rises as the current flows along the paper fibres, energy is dissipated and the resulting heat chars the papers and compound in the manner shown in Figs. 47, 48, 49 and 50.

The probable consequence of such action can be

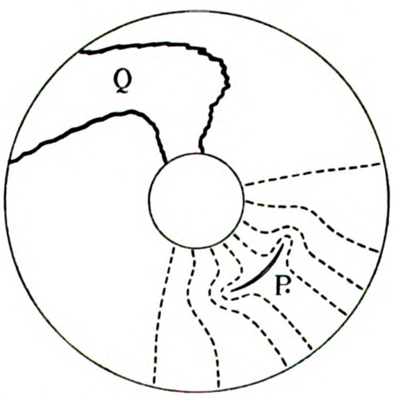

FIG. 51.—Effect of irregularity on dielectric current.

illustrated as follows. If we lay a small cylindrical electrode on a layer of, say, half a dozen impregnated papers which in turn are lying on a flat metal plate, and then apply a pressure of, say, 10 000 volts between the electrode and the plate, we find that after a few hours the free compound has been driven from the upper paper for a space of $\frac{1}{2}$ in. or so all round the electrode. The compound travels across the direction of the field from parts where its strength is high to parts where the field is weaker. It is reasonable to assume, then, that in our hypothetical fault P the compound would be driven away from the edges of the weak patch which would so spread and, given time, ultimately move backwards and forwards, linking up with other similar spots until it opened up an irregular path from the conductor to the sheath. Further supporting evidence for this theory is given by the shapes of charred holes in single-core cable breakdowns. They frequently emerge on the outer surface in a direction oblique to the radius, as at Q.

This same I^2R theory of dielectric losses will explain why during a prolonged test on a 3-core cable the outer core papers become charred where the cores are in contact. It is because the wormings form an inferior contact between the cores; the displacement currents consequently crowd into the line of contact between the cores themselves and in so doing are partially turned from a radial to a circumferential direction, flow along the fibres instead of across them, and so raise the local power factor and heating. Mr. Beaver has shown * that impregnating a 3-core cable made up of previously impregnated papers both on the cores and wormings reduces the power factor. He attributed the difference to the loss in the unimpregnated wormings, but from the consideration advanced in this paper it would appear that in such a case impregnation filled the wormings with compound, created a better contact between them and the cores, and withdrew the displacement current from the line of contact between cores, turning it into directions across the fibres instead of along them. This reduced the conduction losses in the fibres and so lowered the power factor.

The claims of this theory of breakdown in impregnated-paper cables over any theory previously advanced may be briefly summarized by the way in which it explains the following phenomena :—

(i) The presence of the charred patches in isolated places after prolonged test.
(ii) The peculiar designs assumed by the charring.
(iii) The time/voltage relationship.
(iv) The non-recovery, even after cooling.
(v) The shape of burn-outs in thick dielectrics.
(vi) The difficulty in employing the logarithmic formula connecting dielectric stress, dimensions and breakdown voltage.

It is of interest to note, before closing this Section, the bearing which this theory has on the question of intersheaths in cylindrical condensers, such as single-core cables. Suppose that just on the inside or on the outside of the weak spot P there were a metal intersheath. The effect of this would be to alter the shape of the current path in such a way as to reduce the change in stress at the edges of the patch and to turn the currents more into a radial direction. This would reduce the tendency of the weakness to spread, would reduce the

* See Appendix II, (32).

I^2R loss and, without any question of the sheath being held at a definite potential for grading purposes, would strengthen the dielectric simply by its presence.

(X) Assessment of Cable Quality.

A good deal of attention is being given to-day by cable purchasers to the drafting of specifications and tests in order to ensure that the cable shall meet all the conditions of service satisfactorily. These activities may be broadly divided into :—

(i) Instructions to the cable maker as to the making of the cable.
(ii) Details of tests to be applied to the finished cable.

Under (i) naturally fall the general design of the cable, the thickness of dielectric between cores and between cores and earth, the thickness of lead, type and number of armouring wires, details of serving, etc. It was usual, until recently, to specify the paper, but it is now generally appreciated that the established views on this material are not necessarily the correct ones, and that the cable maker is in the best position to settle the matter. The compounds to be used are also sometimes indicated, but, apart from fixing the design or approving a design submitted by the cable maker, there is a good deal to be said for matters under (i) being left to the manufacturer.

In considering (ii) above, it will be appreciated from the previous contents of this paper that the tests which are suitable for cables to work on lower voltage are no longer suitable at **33 000** volts and upwards. The dielectric-resistance test certainly indicates the dryness of a cable and, in spite of its obvious academic weakness as shown in the early Sections, is a valuable test of quality of a finished cable. It has become fashionable during the past few years to decry high resistance values, and certainly a cable with a high dielectric-resistance 1-minute value may be an inferior cable as regards performance. At the same time, a high value of dielectric resistance is not in itself evidence of bad quality. The important question to determine is whether the cable suffers in other respects owing to the means which have been taken to produce the high resistance, but there are other tests to show up this factor.

Dielectric-loss tests are rightly established as a criterion of quality, but it should be remembered that they only indicate the average condition over the length of the cable and may not show up a local weakness. Also, a low dielectric loss may be obtained by the use of a compound so thin that, after some months of service, parts of the cable are drained dry. In taking dielectric-loss tests it is usual to watch the increase of power factor with voltage, but in view of the uncertain effects of heating already demonstrated no very stringent conditions can be imposed in this respect at present. Loss tests over a temperature range are sometimes called for and these may be taken with the cable on a drum immersed in a tank of water or with the cable heated electrically while laid out on the ground. The former is the more satisfactory method. Laying out a drum length and recoiling it on to the drum is not calculated to lengthen the life of a super-tension cable which is afterwards to be laid a second time before being put into operation. Current heating also gives very uncertain results compared with water heating, owing to the temperature of the dielectric not being known with any degree of accuracy.

The author will not presume to frame tests, but there are two guiding principles which might receive more attention by purchasers in selecting tests for use in accepting high-voltage cables.

(A) The tests which may shorten the subsequent life of the cable in service should as far as possible be restricted to special test-pieces not to be used afterwards.
(B) The object of using high-voltage cables is to lower transmission costs, and this object is partially defeated when the tests are made unnecessarily complicated and expensive, as the cost of the tests must be added to that of the cable. Tests on the thermal properties of a drum length, for instance, are very interesting but, in view of all the other factors, are of minor importance to-day for acceptance purposes.

APPENDIX I.

Determination of Constants in the Expression $I_t = I + At^{-n}$.

Two alternative methods employed in this paper to determine the absorption constants from a curve of charging currents are shown below. In the first method

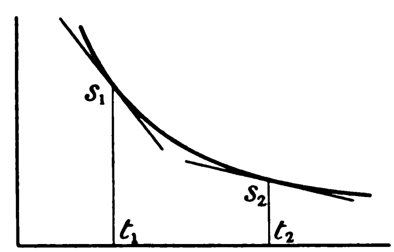

Fig. 52.—Determination of absorption constants.

(*a*) the curve is drawn out on a large scale and tangents are drawn at definite points. The use of the logarithms of the ratio of slopes and inverse ratio of times gives the value of the index n. I follows simply. In the second method (*b*), which is more cumbrous but more certain than method (*a*), the value of I is first determined by trial, or, if equal time ratios are taken, by a simple arithmetical expression, when n follows as before from a ratio of logarithms.

(*a*) *By slopes* (see Fig. 52).

$$I_t = I + At^{-n}$$

Slope $S = \frac{dI_t}{dt} = -nAt^{-n-1}$

$$\therefore \frac{S_1}{S_2} = \left(\frac{t_2}{t_1}\right)^{n+1}$$

$$\log (S_1/S_2) = (n+1) \log (t_2/t_1)$$

$$n = \frac{\log (S_1/S_2)}{\log (t_2/t_1)} - 1$$

$$A = \frac{S_1}{-n} t_1^{(n+1)}$$

$$I = I_t - At_1^{-n}$$

If $t_2 = 2t_1$ then

$$n = \frac{\log (S_1/S_2)}{0 \cdot 301} - 1$$

(*b*) *By calculation.*

Three points on the curve will give

$$I_{t1} = I + At_1^{-n} \quad . \quad . \quad . \quad . \quad \text{(i)}$$

$$I_{t2} = I + At_2^{-n} \quad . \quad . \quad . \quad . \quad \text{(ii)}$$

$$I_{t3} = I + At_3^{-n} \quad . \quad . \quad . \quad . \quad \text{(iii)}$$

Equations (i) and (ii) give

$$\frac{I_{t1} - I}{I_{t2} - I} = \left(\frac{t_2}{t_1}\right)^n \quad . \quad . \quad . \quad . \quad \text{(iv)}$$

Equations (ii) and (iii) give

$$\frac{I_{t2} - I}{I_{t3} - I} = \left(\frac{t_3}{t_2}\right)^n \quad . \quad . \quad . \quad . \quad \text{(v)}$$

Therefore

$$\frac{\log \left(\frac{I_{t1} - I}{I_{t2} - I}\right)}{\log \left(\frac{I_{t2} - I}{I_{t3} - I}\right)} = \frac{\log \left(\frac{t_2}{t_1}\right)}{\log \left(\frac{t_3}{t_2}\right)} \quad . \quad . \quad . \quad \text{(vi)}$$

I can be determined by calculating the value of the right-hand ratio and interpolating on a curve obtained by plotting trial values of I against resulting values of the expression on the left-hand side.

The operation of determining the constants by calculation is simplified by making

$$t_2 = 2t_1$$

and

$$t_3 = 2t_2$$

For instance, 1-, 2-, and 4-minute values are convenient.

Then

$$\frac{t_2}{t_1} = \frac{t_3}{t_2}$$

and

$$\frac{I_{t1} - I}{I_{t2} - I} = \frac{I_{t2} - I}{I_{t3} - I}$$

so that

$$I = \frac{I_{t2}^2 - I_{t1}I_{t3}}{2I_{t2} - (I_{t1} + I_{t3})} \quad . \quad . \quad . \quad . \quad \text{(vii)}$$

Having determined I then n follows from Equation (iv) thus:—

$$n = \frac{\log \left(\frac{I_{t1} - I}{I_{t2} - I}\right)}{\log (t_2/t_1)} \quad . \quad . \quad . \quad . \quad \text{(viii)}$$

and A is obtained by substituting $t_1 = 1$ in Equation (i) whence

$$A = I_{t1} - I \quad . \quad . \quad . \quad . \quad . \quad \text{(ix)}$$

APPENDIX II.

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(32) C. J. BEAVER: "Some Points in the Manufacture and Installation of High-Voltage Cables." Paper read before the North-Western Centre of the I.E.E., 31 March, 1925.

(33) H. W. MALCOLM: "The Theory of the Submarine Telegraph and Telephone Cable."

(34) C. RUNGE and H. KÖNIG: "Numerisches Rechnen" (Berlin, 1924).

(35) J. HOPKINSON and E. WILSON: *Philosophical Transactions of the Royal Society of London*, 1897, vol. 189, p. 109.

(36) G. W. PARTRIDGE: "Rises in Pressure and Protection of A.C. Circuits," *Electrical Review*, 1924, vol. 94, p. 992.

DISCUSSION BEFORE THE INSTITUTION, 5 NOVEMBER, 1925.

Mr. S. W. Melsom: I am inclined to agree with the author's theoretical treatment of the subject. No doubt a great deal more experiment is required before his theory can be adopted, but nevertheless it does seem to me to be established that it is essential, in dealing with such a difficult matter as dielectric losses, that one should study the question from the dielectric point of view and investigate the behaviour of the material of the dielectric under all conditions of stressing. That is what the author has endeavoured to do, and on that basis there should be some explanation of the difference between a.c. and d.c. phenomena. The dissipation of the widely accepted theory as to the relation of d.c. conduction losses to a.c. dielectric loss at the high temperatures is particularly valuable, but here again it is clear that the last word has not been said, and it seems probable that a study of Evershed's paper on "The Characteristics of Insulation Resistance" * might help to a solution of the point. Towards the end of the paper the author goes very briefly into the question of the assessment of cable quality. With a great deal of what he says in that connection I do not wholly agree, and I feel that that section might very well be amplified.

Mr. L. Emanueli: In my opinion it is not necessary to emphasize the result of the theory of dielectric absorption, which shows the strict relation between d.c. and a.c. tests, and probably, from lack of better knowledge of dielectrics from the experimental point of view, we must agree that this theory is simply an attempt to solve the problem. Unfortunately, the physical theory of what is happening in the dielectric, which ought to be the ground on which the mathematical theory can be built up, is rather unknown and uncertain. For this reason we must appreciate the present paper, especially that part which deals with the effect of moisture. The author's experiments give support to the theory according to which the absorption phenomenon is due to the presence in the dielectric of electrolytic ions moving amongst the molecules. I think that this theory is the most probable one. With reference to the "V" curve of dielectric loss, I also plotted several of them using a very low voltage gradient in the dielectric. With only 100 or 200 volts on a cable constructed for any working pressure, one can be absolutely sure that ionization in the air films is absent. The curves which I obtained on cables at different frequencies ranging from 22 to 1 000 cycles per second show a "V" shape similar to that which is well known (see Figs. A and B), but below the ordinary temperature, say 15° C., with decrease of temperature the power factor increases to a maximum and then diminishes again. The maximum corresponds approximately to zero Centigrade. The behaviour of the dielectric at different frequencies is also very interesting. The minimum points of the "V" curves appear to lie on a line parallel to the abscissæ. The power factor diminishes when the frequency increases at high temperature, and increases when the frequency increases at low temperature. In a set of curves taken on the compound alone it diminishes again with increase of frequency at very low temperatures. This is certainly not in accordance with the von Schweidler and Granier theory, in which the power factor appears always to diminish when the frequency increases. The experimental part of the paper does not appear to be complete enough to show it. Heavy

* *Journal I.E.E.*, 1914, vol. 52, p. 51.

mineral oil shows a similar behaviour, but the minimum of the "V" curve appears to be shifted to a lower temperature than for compound. Adding to the oil a different percentage of rosin, the minimum moves always towards the high temperature. Coming now to the behaviour of the dielectric of the cable at high-voltage gradients, I am afraid a complete explanation of what takes place cannot be found in what the author states. I would first mention that the compound itself, and in general all the fluid and semi-fluid dielectrics, show an increase of power factor with the voltage gradient. Mineral oils show a maximum in the power factor which varies inversely with the temperature, i.e. the higher the temperature the lower the voltage at which this maximum appears. The variation of the power factor is also greater in oils which have been heated for a long time in the presence of copper. The most important question in high-tension cable-making is the change of power factor due to air or gas trapped in the insulation. It is certainly true that the so-called ionization curve gives an exact idea of the impregnation of a cable, and it enables one to reject bad cable which would break down in service sooner or later. Although I agree with the author that it only gives an average idea of the impregnation of the cable, in practice perhaps the results of other tests have made me rather sure that the average test is quite safe. It is worth while to note that in considering ionization curves one has to take into account the temperature of the cable, because the influence of the ionization on the value of the power factor varies very considerably with the temperature. At very low temperatures this influence is great; then it diminishes if the temperature increases, owing to the fact that the compound expands and fills up the empty spaces. Above 50° C. the power factor increases when the pressure increases, because the power factor of the compound itself increases. This I proved in my paper read before the last International Conference on Extra-High-Tension Lines in Paris. I believe that a more important point in the paper is that referring to the breakdown of the cable insulation as a consequence of the migration of the compound. I do not think that it is due, at least to a great extent, to the lack of uniformity in the insulation, but chiefly to air or some other gas present in the form of a film between the paper layers. It is very easy to make the following test: Take two electrodes, a metal plate and a needle; on the plate lay a number of sheets of paper impregnated with a cable compound in such a way that between the needle and paper remains a small gap (0·1 in.). If an increasing tension is applied to the electrodes, at a certain value of the voltage the compound is thrown away as though from the needle there issued a powerful current of air towards the plate. The paper sooner or later dries in front of the needle and breaks down. This is a sort of bombardment of the impregnated paper by the ions emitted by the needle. In a cable we do not have needles but in their place we have gas pockets which at a certain tension become ionized. It is easy to see what is happening in those air pockets if we make another test and observe an air film left between an impregnated-paper sheet and the flat bottom of a glass container, the two electrodes being a metallic disc underneath the impregnated paper and some water in the glass container, through which one can see what is happening. The phenomenon is identical to that of the needle, only instead of one needle there are many of them built up in the air film. These at low tension are

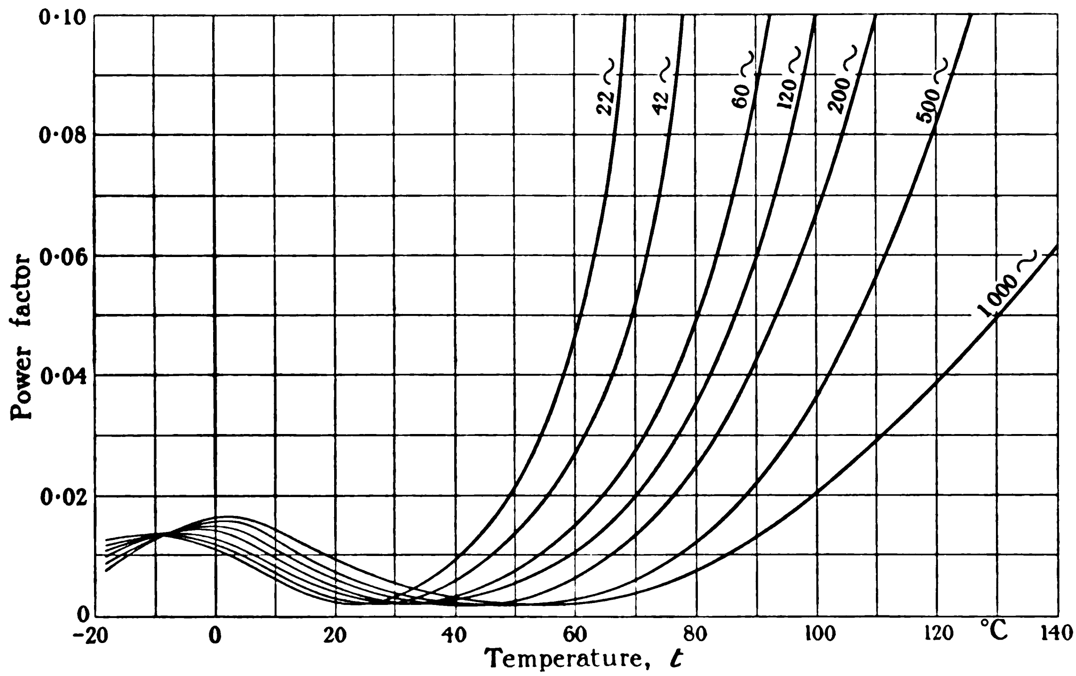


FIG. A.—Variation of power factor with temperature of an impregnating compound at various frequencies.

wandering from point to point, but at higher voltages fix themselves in definite spots and start to throw away the compound from the paper all around. The compound thrown away takes on a white, frothy appearance, and in some cases also alters chemically. The paper first becomes charred and then breaks down. It is possible to obtain also the tree-shaped marks which are often noticeable in a cable core after a long-period voltage test. I will not say that this is the only way in which cable breakdown occurs but I think it is the most probable one. In Italy there is a cable in successful operation at a working pressure of 130 000 volts. This was first put in commission there over 18 months ago. Its construction differs from that of an ordinary cable only in the fact that air or gas bubbles are entirely eliminated from the insulation. With reference to the inspection test on extra-high-tension cables, I think the matter cannot be settled now, the construction of extra-high-tension cables not being advanced enough to enable well-defined rules to be generally agreed upon. I have not much faith in a low-tension d.c. test.; on the contrary I believe in an ionization test properly studied and well determined, taking into account the temperature. I think that the amount itself of the dielectric losses is of no practical importance at all. Reduction in the amount of losses at high temperature is also not very desirable. As a matter of fact in the United States, where cables impregnated with vegetable oil showed enormous values of power factor, they went to the opposite limit, prescribing a very low power factor at high temperatures. This forced manufacturers to use oils which at high temperatures are very thin and which very easily drain into the lower part of the cable, leaving in the upper part big air pockets. I do not think it advisable to measure power factor, using current in the conductor to heat the cable, but would recommend a proper constant-temperature bath. As heating cables to high temperatures spoils the impregnation, I would also recommend that lengths thus heated be not used in actual service. I hope that the whole question will be considered carefully both by the users and by the cable makers, and that some reasonable rules for testing will be agreed upon in time.

Mr. H. A. Ratcliff: A very large portion of the paper is devoted to an explanation of dielectric charging phenomena, and although the information given may not afford much comfort to cable users it certainly does throw light on many of the obscure actions taking place in an extra-high-tension cable. I am particularly interested in the author's views on the connection between the I^2R loss in a dielectric and the so-called hysteresis loss, because when investigating the subject of dielectric loss about 10 years ago I was very much impressed by the possibility of some such connection between the two phenomena, and, moreover, it is only fair to the author to say that opinions expressed recently by investigators in America very largely support his theories. So far as the purely theoretical aspect of dielectric phenomena is concerned, the well-known "V" curve appears to provide one of the most valuable sources of information and therefore in this connection the author's explanation of its characteristic shape merits serious consideration, and is certainly a very valuable step in advance, for it is an extraordinary thing that, although the shape and general characteristics of the "V" curve have been

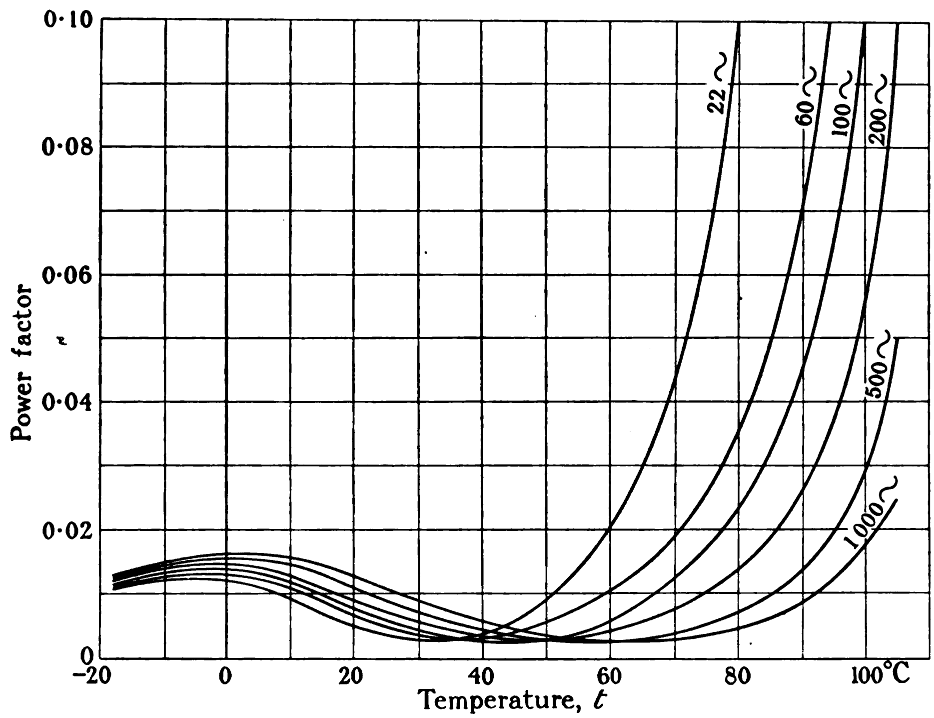


FIG. B.—Variation of power factor with temperature of a cable at various frequencies.

known for years, the real nature of the change which it indicates has never been discovered. Reverting to matters more closely associated with the behaviour of cables under actual working conditions, the author rather emphasizes the importance of the "time/voltage" curve and appears to imply that it explains the breakdown of cables many months after laying. Provided that a cable is constructed so as to have a sufficient factor of safety, I am in the light of actual experience inclined to question this explanation, and in any case it is of little real value unless due consideration is given to the conditions arising from load variations. The factor of safety also has an important bearing on pressure tests. Pressure tests on full drum lengths of cable either before or after laying are merely for the purpose of detecting defects arising during manufacture or laying and the pressure applied should be well within the limits covered by the factor of safety. It is obviously very desirable that cables should be capable of withstanding this requirement, and moreover, the factor of safety of the dielectric should certainly not be less than 2, and preferably more, since a pressure approximating to double the normal working pressure is liable to arise from ordinary switching operations. For example, a cable which would be capable of withstanding a reasonable amount of rough handling and the temperature-changes arising from load variations would, if its breakdown pressure followed a time/voltage curve having an asymptotic value of 66 000 volts, make a thoroughly sound cable for use under normal operating conditions on a 33 000-volt system. Tests which are intended to stress, and ultimately break down, the dielectric should only be conducted on comparatively short experimental lengths of cable. The author's estimate of a reasonable factor of safety under ordinary cable-operating conditions would be both of interest and value. It is not of much interest to the cable user to know that a hypothetical cable will, given ideal conditions, survive for centuries. What he wants is a cable which will last, say, at least 25 years under ordinary operating conditions. The effects of transient high-voltage phenomena are apt to be somewhat overrated, and when they occur there is usually some fairly definite explanation of their origin. In the case of the undertaking with which I am associated all spark-gaps and similar devices on the 6 600-volt system have been scrapped, and so far as I am aware some "over-voltage" or "lightning" dischargers installed on the 33 000-volt system have rarely, if ever, functioned, although set to discharge at rather less than double the working pressure. I am of the opinion that the cables themselves are the most effective absorbers of transient high-frequency disturbances on the system. With reference to the nature of cable breakdowns I agree that the maximum-stress theory has little or no bearing on the actual behaviour of cables in practice, although in this connection many cable manufacturers appear to have rushed to the other extreme and reduced the thickness of the dielectric core wall on 33 000-volt cables before they were thoroughly familiar with the numerous factors involved, and it is therefore significant that they are now increasing the thickness of the core walls. In the case of three-core cables the ultimate breakdown appears to arise as much from mechanical as from electrical causes, although with this form of construction the tangential-stress theory of Höchstädter is by no means lightly to be ignored, since it undoubtedly has some bearing on the behaviour of 3-core cables, and in this connection it is perhaps significant that I have yet to experience a breakdown of a single-core cable. I cannot agree with the author's views on the correct method of conducting a dielectric heating test. It is quite wrong to immerse a drum of cable in a tank of hot water for this purpose. There appears to be little, if any, doubt that the effects of temperature gradient in the cable dielectric, and the electromagnetic effects arising from the currents circulating through the conductors have an important bearing on the behaviour of the dielectric, and, therefore, if for this reason only, it is essential that dielectric heating tests on drum lengths of cable should be made by applying pressure (normal or excess) to the conductors while passing through them, from a separate low-voltage source, heating currents of the necessary extent. In the case of 3-core cables carrying balanced three-phase currents, there is no reason why a test of this nature cannot be carried out with the cable coiled on a suitable drum.

Mr. N. A. Allen: The charging curve of a cable is assumed on page 102 to be of the form $I + At^{-n}$, where the index of time, n, is assumed itself to vary with time. It

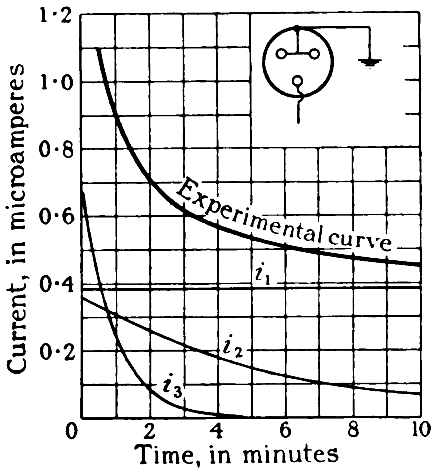


FIG. C.—Charging curve of a 0·3 sq. in. 3-core 6 600-volt cable tested at 1 000 volts.

$$\begin{aligned} I &= i_1 + i_2 + i_3 \\ \left.\begin{aligned} i_1 &= 0{\cdot}3855 \\ i_2 &= 0{\cdot}359\epsilon^{-0{\cdot}171t} \\ i_3 &= 0{\cdot}685\epsilon^{-1{\cdot}093t} \end{aligned}\right\} &\times 10^{-6} \end{aligned}$$

is difficult to get a true physical conception of this change of the time index with time, and moreover it involves certain difficulties with the mathematical solution of the problem. I should like to ask the author whether he has attacked the question of charging currents in the new light shed by the late Dr. Steinmetz's recent paper.* In brief it may be proved that any charging curve for a composite dielectric may be analysed into the sum of a series of exponential curves having various time indices and it is always possible to fit the experimental curve

* C. P. STEINMETZ: "Cable Charge and Discharge," *Transactions of the American Institute of Electrical Engineers*, 1923, vol. 42, p. 577.

mathematically correctly, provided the number of transients is chosen properly. Fig. C shows a charging curve on a 6 600-volt cable where the sum of three transients satisfies the curve. The correct equation for any period of time whatever is given in full. Fig. D shows a charging curve on a low-tension cable where the conditions are such that four transients satisfy the curve. In Fig. E one of the curves given by the author in Table 16 is worked out. Four transients appear to satisfy the observed experimental curve in this case. It will be observed that in each

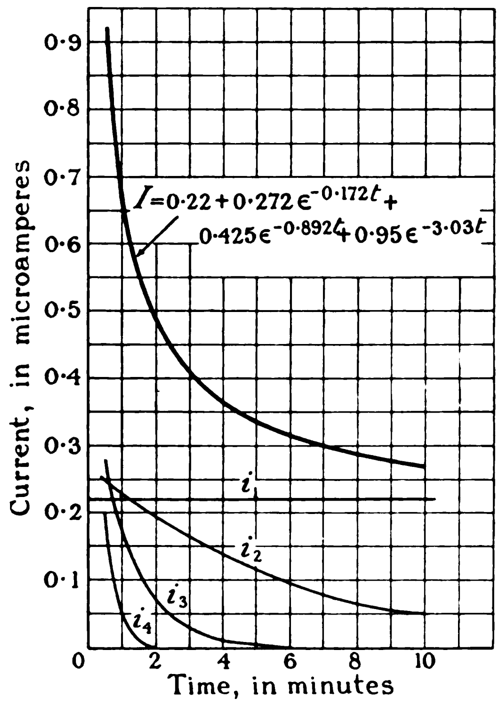


FIG. D.—Charging curve of a 0·75 sq. in. single low-tension cable tested at 1 000 volts.

$$I = i_1 + i_2 + i_3 + i_4$$

$$\left.\begin{aligned} i_1 &= 0{\cdot}22 \\ i_2 &= 0{\cdot}272\epsilon^{-0{\cdot}172t} \\ i_3 &= 0{\cdot}425\epsilon^{-0{\cdot}892t} \\ i_4 &= 0{\cdot}950\epsilon^{-3{\cdot}03t} \end{aligned}\right\} \times 10^{-6}$$

case the first transient, i, is independent of time and must therefore be the steady leakage current which would continue to flow after a long period of time. We therefore have a ready method of finding the true insulation resistance of a cable, by taking readings of charging current over short periods and finding the true leakage current by analysing into the Steinmetz transients. I would suggest that this provides a very easy and accurate way of comparing the quality of different cables. In Fig. 27 the author gives two curves for cables made up with different impregnating oils. It is not stated whether the curve having a high minimum point but a more gradual slope was taken with a heavy oil and the curve with a lower minimum but a steeper slope with a lighter oil, but this is a phenomenon which sometimes occurs. It may be that the explanation of this is connected with the infinitesimally small air bubbles occluded in the insulation. These air bubbles are quite different from the air films and pockets which occur in a badly made cable, they may exist among and even inside the actual fibres of the paper, and it is by no means certain that if they exist they are necessarily deleterious, owing to their extremely high electric strength. On the hypothesis that such finely divided air exists in cable even of the best manufacture as known at present, with a heavy oil the oil expands and compresses the air as the temperature rises, so raising its dielectric properties and reducing the loss to a minimum. As the oil becomes less viscous with rising temperature, the air can expand more and more freely; thus the losses increase as the air pressure falls, and moreover this effect is augmented by the increasing a.c. conductance. In the case of a thin oil the same argument explains the "V" curve, and also why the curve is steeper, since the air can expand much more freely. The author states that there is

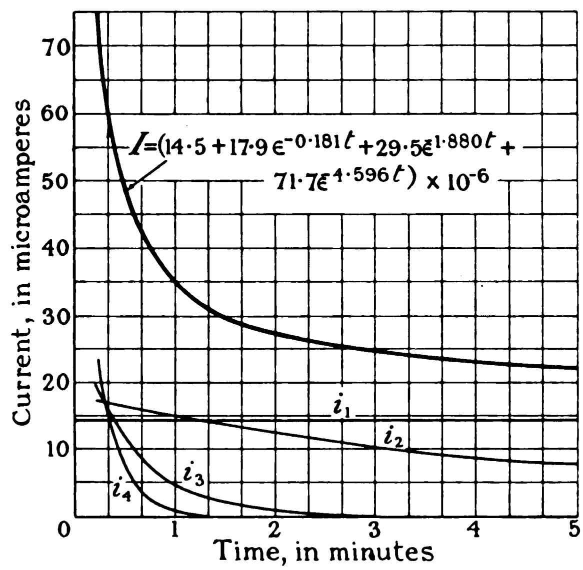


FIG. E.—Analysis of charging curve of a 0·2 sq. in. low-tension cable tested at 500 volts and 50° C.

$$\left.\begin{aligned} i_1 &= 14{\cdot}5 \\ i_2 &= 17{\cdot}9\epsilon^{-0{\cdot}181t} \\ i_3 &= 29{\cdot}5\epsilon^{-1{\cdot}880t} \\ i_4 &= 71{\cdot}7\epsilon^{-4{\cdot}596t} \end{aligned}\right\} \times 10^{-6}$$

little difference between the breakdown voltage of a long length of cable and a 5-yard sample. In view of the large numbers of references in recent literature to the so-called hot-spots in a cable, at which presumably the cable ultimately breaks down, it would seem that the electric strength of a 5-yard sample would depend largely on whether or not there were an incipient hot-spot in that 5 yards. The smoothness of the curve in Fig. 44 seems to negative this, but it would be of interest to know whether the curve represents a mean value of the results of many tests.

Mr. A. M. Taylor: The author's statement in reference to intersheaths on page 122 and in connection with Fig. 51, viz. that the intersheaths reduce the risk of breakdown, interests me very much. I am glad to find that he agrees with me as to the advantage afforded by intersheaths in this respect, which I have long maintained. There is another advantage which is not so fully appreciated, viz. that intersheaths tend very

materially to stop the puckering of the paper when the cable is bent; or, conversely, permit of a greater depth of insulation for equal puckering. I am surprised that some recent super-tension cables, to be used in America, have apparently been designed in total disregard of this factor. A very great authority on cable manufacture told me three years ago that it was impracticable, on account of this puckering of the paper, to *make* single-core paper cables if the depth of insulation exceeded a certain amount. No puckering occurs until after the second intersheath has been reached, a distance from the centre of the cable of quite 50 per cent in excess of that indicated by the authority referred to above. This result has no doubt been obtained by the use of intersheaths. It will be noted that the puckering is in parts so severe as virtually to form radial paths on the line of cleavage of the insulation, thereby greatly weakening the dielectric strength at this part. It ought to be mentioned that this puckering will be prevented on future cables, but at any rate the fact has been established that the intersheaths have this very valuable property. Another advantage of intersheaths, and a very important

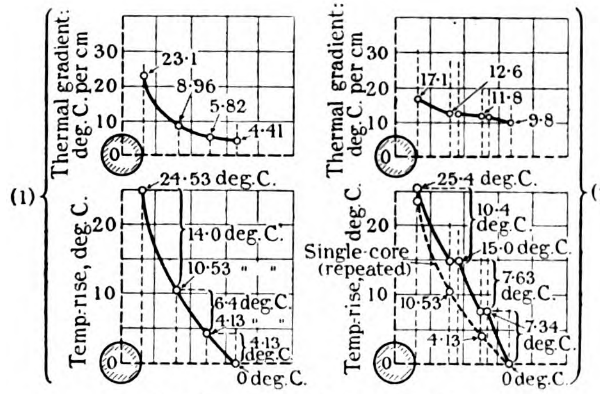


FIG. F.—Thermal characteristics.

(1) Single-core cable for 41 000 kW.
(2) 3-core concentric cable for 104 000 kW.

one, is that the thermal gradient across the innermost dielectric, due to the load current, may be controlled and greatly reduced below what it would be if there were no intersheaths, resulting in a considerably increased carrying capacity. For instance, in Fig. F it will be noticed that there are only 10·4 deg. C. across the innermost dielectric in a 0·15 sq. in. triple-concentric cable transmitting 104 000 kW; whilst there are no less than 14 deg. C. across a corresponding thickness on the single-core cable transmitting only 41 000 kW, both cables having the same overall diameter. If the load on the right-hand cable were reduced to 41 000 kW there would be only 1·61 deg. C. across the innermost dielectric, as compared with 14 deg. C. across the corresponding slice of the single-core cable. The importance of this control over the temperature of the innermost parts of the cable, only needs to be pointed out to be appreciated. One more advantage of intersheath cables is of considerable importance, viz. that each section of the cable can be tested separately. This feature enabled me to discover that there was insufficient impregnation in my intermediate insulation, a defect which will be easily remediable in future cables. With reference to my earlier remark, I would call attention to the author's statement on page 121, viz. "The charred condition is restricted neither to the proximity of the conductor nor to that of the lead," which agrees with the tendency to pucker (even before bending) that undoubtedly exists where there is a considerable depth of insulation without any intersheath. It may be also that the results observed by Mr. Fernie, viz. that the dielectric was in some cases weakest at the circumference, may have been due to the same cause.

Mr. H. C. Silver: I am most interested in the Section dealing with the resistance of the cable, and I should like to ask the author whether he thinks more attention should not be devoted to the subject of resistance, so that by this means we might eliminate the testing of cables for breakdown pressure. Further, I suggest that the progress of our knowledge of dielectrics would be greater if we devoted more attention to the measurement of resistance and less to the determination of what is known as "electric strength." The author has suggested a theory of cable breakdown, and I should like his views on the following: It is known that chemical action cannot take place unless moisture is present, and it is believed that this must be in the form of an electrolyte. Is electrical breakdown a chemical action and merely the result of passing current through the dielectric, thereby converting it into a conductor?

Mr. G. L. Addenbrooke: Dielectrics are one thing and dielectrics made up into cable are to some extent a different thing. Certain conditions which necessarily occur in cables are not present when dielectrics are tested in perfectly even fields. That is a point which very greatly complicates any question of finding final explanations. I wish to speak chiefly on the question of explanations or theories of dielectrics. Some years ago I discussed with the late Sir James Dewar the question of what could be done to investigate the fundamental problems of dielectrics, when he said: "Experiments on dielectrics will be worthless unless they are made on some perfectly definite chemical substance." There is a great deal in that point of view. Every substance behaves in certain definite ways in electric fields and if two substances are mixed together the action on each of those may be different, and a compound result is obtained. I feel that that is to some extent an explanation of the dip in the curve to which the author devotes a good deal of attention. In some lectures I gave six years ago I showed a curve of that description, which was originally obtained in Glover's works in 1906, but at that time it seemed so curious that we thought there was a mistake in our readings, and therefore I did not deal with it or publish anything about it until the time of my lectures, when the British Insulated Wire Co. supplied me with some cable data in which that curve occurred. I asked them if they had any explanation of it, and they replied that they thought it was due to increase of pressure in the cable as it became heated. Mineral oils, of course, expand very considerably on heating, and the lead does not expand so much, so that the heating would be less on the outside. At the same time, they said they were not altogether

satisfied with the explanation, and asked if I could suggest any other. I did think of another explanation, which I discussed with the late Bertram Blount, the chemist. This explanation is based on some results which I gave in those lectures to which I have referred, and which I repeated in *Nature* about 18 months ago. My experiments were in drying a dielectric, taking its electrical properties and then allowing small weighed percentages of moisture to diffuse into the dielectric. I then ascertained the effects of those extra percentages of moisture. I found that when the amount of moisture is very small the losses go up very nearly as the percentage of moisture increases, but after a certain point the curve begins to rise rapidly, that is to say, the losses are greater than the proportionate increase in the moisture. What appears to happen in drying is that the drying tends to draw the moisture out of the material and, on the other hand, the material tries to retain the moisture. The result is a certain equilibrium. There may be one equilibrium for oil and another for paper, which has a very large surface. The paper can be dried to a very great extent by passing dry air through it, heating it and so on. The hot paper is brought into contact with the oil, and they both cool together. There is a certain vapour pressure in each, and the question is whether the vapour pressure is equal in both or whether there is a tendency for the moisture in one to get absorbed into the other. I am under the impression that in those circumstances a good deal of the moisture which is in the oil when it is warm will go into and settle down in the paper as the oil cools, and that will cause the paper and the cable as a whole to have a heavier loss than it would have if the moisture were equally diffused. When the current is switched on and the cable starts to heat up, the paper gives up its moisture and it diffuses into the oil and the losses are reduced up to a point. I do not say that is the whole of the explanation, but I think that it is part of it. It is also the case, I think, that with increased pressure the losses would be diminished. That is a matter which, at any rate for submarine cables, was studied very carefully as long ago as 1860. It was found that putting a pressure of 3 tons per sq. in. on cables increased the resistance six times at the same temperature, but the capacity was not appreciably altered. I believe those tests have been carried out again within the last year or two and have been confirmed, but they are not mentioned in textbooks and the fact that pressure has a great effect on resistance and not on capacity is overlooked. I have no doubt it has also an effect on the alternating losses, but very little on capacity, though I know of no experiments which so far have been tried. That, I think, is one of the points which lead to the belief that absorption losses are due to the presence of moisture or electrolyte and not to a property of the material. The author has spoken a great deal about resistances and capacities in series or parallel. Many years ago I spent time on this subject, but I believe that Curtis of the Bureau of Standards has shown that, if extended, similar results do not agree with what is actually found in practice. Again, supposing the actions are imitated by means of resistance and capacity, what progress has been made? What we want is a real physical explanation, and the explanation referred to above only substitutes one incomprehensible idea for another which is really more incomprehensible.

Mr. W. D. Owen: The author has explained how he has been led by Schweidler, Granier, and others, to a conception of a.c. power loss as a joulean loss due to absorption current and normal conduction current flowing in a Maxwell network of capacities and resistances. This conception does not account for the distortion of wave-form which takes place with some dielectrics, such as glass.* Can a modified quantitative theory be formulated on the lines of the author's argument which may include distortion? The author's statement on page 119, that: "This time effect is quite a new phenomenon and so far very little has been published on the subject," calls for some comment. My own work on this subject [see Appendix II (26)] is based on the laws published by Peek as far back as 1915, and there can be little doubt that Peek adopted the same method of extrapolating to "infinite time," although there does not appear to be any evidence that the significance of the resulting conclusions is even now fully appreciated. Whatever criticisms may be levelled against methods which make it possible to extrapolate to infinite time on the assumption that the law holds, there can be no denying the value of the revelation that the rate of decrease of electric strength with time is not constant for all materials but differs appreciably. Two materials A and B have similar breakdown values when tested in accordance with present-day accepted standards, but one falls off with time at a greater rate than the other. Presumably the watt loss per unit volume is greater, or its thermal resistance is higher and the influence of the pent-up heat is cumulative. Whatever the reason may be, the "endurance" of the two differs, and a stress such as one can withstand satisfactorily for many years may conceivably rupture the other in a few days. Factors of safety based on a comparison of the 1-minute breakdown values of dielectrics cease to apply after 1 minute has elapsed. What, then, is meant by the term "factor of safety" in relation to dielectrics? Many electrical engineers interpret it as the ratio between the short-time strength and the long-time stress thus: An insulator having a 1-minute breakdown value of 100 kV is put in service on a 20-kV system and is said to have a factor of 100/20, i.e. 5. Herein lies the explanation of "the failure of super-tension cables many months after installation" (p. 119). The same, of course, applies to insulation other than that on cables that suddenly "sits down" on the job after spectacular tests before assembly and possibly after many months of service. The author's frank admissions relative to the past are the finest possible guarantees for the future, and his example is one that might well be followed by others.

Mr. E. A. Beavis (*communicated*): The efficacy of d.c. tests of prolonged duration and periodic reversals at a constant potential of 1 000 volts or so, has long been proved in dealing with gutta-percha cables; undoubtedly it is the most useful method of showing up incipient faults in the dielectric. Extreme care and concentration is essential in such tests over the whole period, and it is

* W. M. Thornton: *Proceedings of the Physical Society of London*, 1911–12 vol. 24 p. 301.

insufficient merely to note readings at 1-minute intervals since defective insulation may only create in the first instance a slight irregularity or temporary holding up of the gradually falling deflection—possibly only for a few seconds—which may pass unnoticed unless attentive watch is kept throughout. It would seem that there is scope for a similar procedure for high-voltage cables; the usual 1-minute d.c. results are useless except for commercial comparison and record purposes, and there is urgent need for factory tests that will discover such potential faults as appear to be impervious to the initial high-voltage a.c. pressures. The use of the "Kenotron" apparatus for obtaining high-voltage electrification curves as a means of discovering incipient faults in power networks has proved successful to some extent, and suggests the possibility that the solution of the problem lies in some form of prolonged steady-potential test. In dealing with the question of power factor and voltage the author has suggested that the true power factor will be equivalent to the low-voltage value obtained from the d.c. index n, plus some allowance for ionization. Now the latter appears to be a very indeterminate factor depending upon variable conditions of manufacture, and as such will alter with different cables and most probably with different lengths of the same cable. It does not seem possible, therefore, that any definite relation for general application between power factor and voltage can exist, i.e. each cable length must apparently be treated on its merits. Under these circumstances the equation obtained for $\cos \theta$ at low voltages cannot very well be applied to the variable high-voltage conditions that obtain. There is also another point to be considered. May not partial ionization also take place in the oil or compound at these higher voltages? This has been suggested as the cause of dielectric resistance decreasing at high voltages, apart from any question of occluded air, and if so it tends to complicate the matter still further. The author has indicated the variations in power factor that can be caused by overloading the cable; other investigators have found similar results, but in many cases these were of a temporary nature, the cable returning to its original condition after the lapse of some weeks. It would be interesting to know what happened in the example cited, i.e. whether the deterioration was permanent. With reference to this phenomenon a case that came under my observation may be of interest inasmuch as the effects were dissimilar to those generally experienced. It was discovered more by luck than design, and occurred to a cable sample that had been in the hot tank undergoing loss/temperature tests. The cable in special circumstances had to be removed from the tank when at a temperature of 180° F., and forthwith placed in a cold tank. The normal power factor was much improved by this drastic treatment and remained so for some days; the original value, however, was regained on slowly cooling from the high temperature about a week later. The curves of power factor and voltage for this particular sample are shown in Fig. G. Such results are possibly not of much value save for the purpose of noting the variability of the power factor at normal temperatures and its dependence on extraneous conditions. At higher temperatures the ionization, although no doubt present, does not seem to be so apparent, and results show more stability. There is also another variable in the power-factor equation and this appears to be "time," since in many cases value increases with prolonged voltage application. On the basis of the "V" curve, supposing a reasonable temperature-rise owing to the duration of the test, there should rather be a tendency for the power factor to decrease; here, presumably, is another effect due to ionization. A solution to the enigma of power factor and voltage holds most probably the key to the problems of high-voltage dielectrics. In relation to the variation of dielectric resistance with temperature, it has been stated that the temperature coefficient is not constant over the temperature range for any one time-interval. The author has given two coefficients in each case for the lower and higher temperatures respectively. It is of interest to know whether the change of value is continuous over the whole

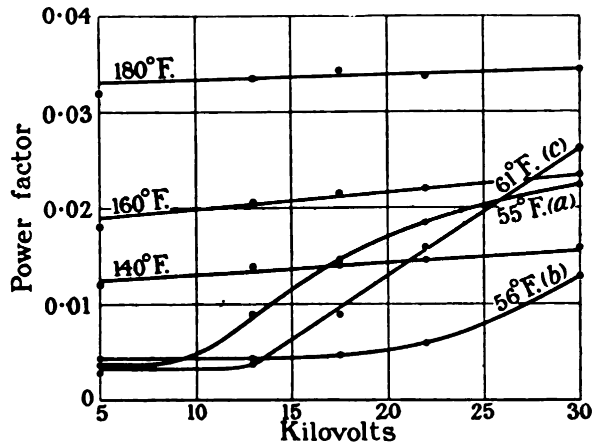


FIG. G.—Variation of power factor with voltage at various temperatures.

(a) Initial test as manufactured.
(b) After sudden cooling from 180° F.
(c) After gradual cooling from 180° F.

range, or whether (as seems probable) it takes place at or about the region of transition, i.e. the melting point of the cable compound. In the latter case the two coefficients can be applied fairly accurately within their respective limits. Any further information that the author can furnish on this point will be welcome.

Mr. R. M. Wilmotte (*communicated*): The paper marks an important stride forward on the subject of dielectric losses, not only for the very valuable data and theories which it gives, but also in making manufacturers realize that to solve the problem and obtain a material improvement in design it is necessary to go down to the fundamental reasons and not so much by collecting a vast array of unconnected data as by scientific thinking. In this respect Mr. Addenbrooke's remarks on experimenting on pure substances are of interest. From his list of references the author has omitted a recent paper by L. Hartshorn * in which a theory of dielectric loss is put forward and leads to a representation by three shunted condensers, similar to those shown in Fig. 6. In this theory the main effect

* *Proceedings of the Physical Society of London*, 1925, vol. 37, p. 215.

is supposed to be due to a contact resistance between the electrodes and the dielectric. This effect appears to have been fairly well established in the case of semi-conductors by the work of Barlow. A further evidence would appear to be given by the effect of pressure on dielectrics. With increased pressure one would expect better contact between the dielectric and the electrodes. This would reduce the shunting resistance of the two outside condensers and thus increase the dielectric loss and reduce the d.c. resistance, and this effect is known to occur. Mr. Hartshorn gives a good deal of other qualitative evidence for his theory, to which might also be added the recent theories on crystal rectification, which are based upon considerable experimental evidence on contact effects. I am not quite clear about the author's explanation of the "V" curve. On page 107 he says: "Each of these imaginary circuits has a distinct power factor ranging from zero with I_1 to unity with I_n (all resistances in series)." Why should the power factor be represented by a resistance in series with a condenser? If the resistance is due to electrolytic action a parallel resistance would appear to give a better physical representation. I should like to suggest the following explanation of the "V" curve. As the temperature rises, the insulation presses against the lead sheath and also on the copper cores. On Hartshorn's theory better contact is obtained and the dielectric loss becomes greater. On cooling, the paper insulation contracts over the copper core, and it is probable that the improved contact on the copper core more than balances the decrease of pressure on the lead sheath, so that the dielectric loss increases on cooling. On further cooling, however, the contact at the lead sheath would become so bad that the dielectric would improve again. If a minimum occurs at about 40° C. it probably means that the paper is exerting about an equal pressure on the copper core and lead sheath at that temperature. Mr. Emanueli's curves, showing how the "V" curves reach a maximum at about 0° C. and then decrease, seem to give good evidence in favour of this explanation. I should like to hear the author's opinion on these points.

[**Mr. C. J. Beaver** also took part in this discussion. The substance of his remarks will be found on page 138 in connection with the discussion before the North-Western Centre.]

[The author's reply to this discussion will be found on page 144.]

North-Eastern Centre, at Newcastle, 9 November, 1925.

Prof. W. M. Thornton: From time to time papers have been read before the Institution that may be called stepping-stones, like Mr. Evershed's recent paper on "Magnets," and that are valuable, not only for the direct information they contain, but for what they point out as unknown. The first step in research is to realize a gap in the subject. The present paper is of value for both reasons. The author shows us the present state of the science and art of cable-making and, further, where this is still imperfect. As I read it, what is still lacking is a connected theory of dielectrics by which certain practical measurements may be co-ordinated, such, for example, as power factor, and the direct- and alternating-current resistances, resistance and the slow change of capacity under direct electrification, breakdown strength and voltage, dielectric loss and voltage, the relation of breakdown strength to frequency, and so on. Several of these may be connected and all of them explained if we regard the rate of change of polarization as the current, and its resistance to motion not in the least resembling the resistance of conductors, which is due to absorption of energy of molecular vibrators from electrons driven by the field colliding with them, but, as the earliest thinkers saw, an "elastic afterworking" due to attraction of polarized molecules, a slow readjustment of electron structure and position after initial polarization. Thus it can be shown that the true resistivity of a dielectric is $\rho = 4\pi v^2/(dk/dt) \times 10^9$ ohms per cm^3,* where v is the velocity of light and k the dielectric constant. Again, in a condenser of capacity c we have $Q = cv$, $I = dQ/dt = c(dv/dt) + V(dc/dt)$. When the voltage is constant $\partial V/dt = 0$ and $I = V(dc/dt)$, so that $dc/dt = 1/R$, the apparent unidirectional resistance of the cable.

Again $W = VI \cos\phi = V^2(dc/dt)$,

or $\cos\phi = (V/I)\ (dc/dt) = r_0/r$

where r_0 is the alternating-current resistance and r the direct-current resistance. The latter in constant when the rate of change of the capacity is uniform, and I have shown that this is characteristic of dielectric polarization in steady fields of force over a long time.* In the above W varies as V^2 when dc/dt is constant, so that the author's result—that the dielectric loss varies as the square of the applied voltage—is an indication that the mean rate of change of the dielectric coefficient with time is independent of the field. I found that the polarization of a rod of insulating material hung in a field approaches the same value whatever the intensity of the field may be.* The expression quoted by the author as given by many investigators for the absorption current is $I_t = I + At^{-n}$. This might well be replaced by one of the form $I_t = I/(1 - \epsilon^{-at})$. At the start when t is small, I is very large. Later it falls to the steady value I.† This has the advantage of using the exponential term directly instead of through Granier's analysis, and no expression in which the index is variable can be regarded as a law unless an expression for the law of variation itself is given. I agree with the author that all the losses can be cast in the form I^2R, but this resistance is not, I think, electrolytic or anything but that due to the internal molecular attraction found equally well in crystalline or fibrous insulators. A

* "The Polarisation of Dielectrics in a Steady Field of Force," *Proceedings of the Physical Society of London*, 1909–10, vol. 22, p. 186; also *Philosophical Magazine*, 1910, vol. 19, p. 390.

* *Philosophical Magazine*, 1910, vol. 19, p. 390.

† "The Lowered Strength of Dielectrics in High-Frequency Fields," *Philosophical Magazine*, 1916, vol. 32, p. 245.

flat-sided hysteresis loop leads to the same law.* The change of loss with temperature is interesting, and the author's results are very valuable. There can be no doubt from the shape of the "V" curves that the author's analysis into two components in Fig. 23 is substantially correct, for no other explanation would seem to fit the curves of Fig. 24, for example. On the polarized molecular basis the argument would seem to be as follows: At moderate temperature there is a certain inter-attraction, and since as the temperature rises the molecules vibrate sideways and in all directions, the poles can be imagined to be shaken a little out of range, and so the loss will be less. At higher temperatures they are driven in the line of the field nearer together for a part of their motion and, since the law of attraction is the inverse square, they then stick together more and cause more energy loss in separation. When they are all driven into contact to form an electrostatic chain, if one electron slips from an atom they slip all along the line and the material breaks down. The nature of cable breakdown discussed in Section (IX) is of the first interest, but I might call attention to the remarkable law—first, I believe, worked out by Kapp but given by me later,† viz. Breakdown thickness $= AV + BV^2$. This fits most dielectrics so closely that it clearly contains the reason for dielectric failure. I regard it as (i) high initial polarization proportional to V, (ii) attraction of polarized molecules according to the square law. One term is purely elastic; the other contains the cause of energy loss and residual charge. There are many other points of interest in the paper. One must admire the method of classifying cables by models, especially if the physical properties of the insulation are varied so that the change due to any component can be seen by the lateral growth of the curves. The problem of thermal conductivity is a further question. We are all indebted to the author for placing this side of the subject before us in so clear and useful a manner.

Mr. C. Vernier: As pointed out by our Chairman in his recent Address, it is quite correct to say that cables lag behind other apparatus as a unit of load capacity, and that the call for higher-voltage cables is becoming more and more insistent. It is pleasing, however, to record that we have in this district carried out much of the pioneer work on high-voltage cables on a commercial scale. It was in 1906 that the first large network comprising some 40 miles of 20 000-volt cables was laid down here. Those cables are still working to-day and have given the very best service during all those years. More recently, some years ago, we adopted reduced thicknesses of dielectric which we believe are not in use anywhere else, the thickness of insulation on 20 000-volt cables being that specified in the B.E.S.A. tables for 11 000-volt working, resulting in a very considerable saving in capital cost. These cables also have given every satisfaction, and are now standard with us for this voltage. A good deal of 66 000-volt cable (both 3-core and single-core) has been laid down and operated during the past 18 months, and whilst it is too early to say that these cables will prove satisfactory, and it is also perhaps an open secret that the first cables operated at this pressure did not come up to expectations, later cables (both 3-core and single-core) have now operated quite satisfactorily for some months under severe conditions. I fully endorse the author's remarks on page 98 regarding the need for improved tests which, while not damaging the cable, will enable the user to discriminate between a cable that will fail within a few months under ordinary conditions of service and one that will continue to stand up satisfactorily over many years. It is unfortunate to have to admit that not one of the present known tests which can be practically applied to very high-voltage cables (say 33 000 volts and over) will reveal serious defects, and users of such cables therefore welcome the author's efforts in his search for one or more such tests. The tests now usually employed comprise: (1) Insulation resistance measurements; (2) measurement of dielectric losses; (3) ionization tests; and (4) breakdown tests and prolonged pressure tests. The futility of the test for insulation resistance as usually performed has been well shown by the author in the first part of the paper, and, in my experience, although such tests are carried out on all cables the results always show great variations between different drums of cables of the same design and manufacture, and no special importance is usually attached to them beyond seeing that the minimum insulation resistance is of a high order. Dielectric-loss tests and breakdown tests have during recent years been the principal tests which have been relied upon to determine the quality of very high-voltage cables. High values for breakdown tests over 15-minute periods are easily attained and cables seldom fail to pass this test notwithstanding that they may later fail and even fail rapidly in service. Dielectric-loss tests are complicated by the sensitiveness of the instruments required for their measurement, the small values of the losses and the highly scientific methods necessary for their correct determination. The buyer or inspector must usually accept a good deal for granted, and, were it not for the very high commercial reputation of our British cable firms, he could place but little reliance upon the results. No independent authority has hitherto been available for checking these results in this country, but I believe that the National Physical Laboratory will shortly be fully equipped for this purpose, if it is not already in a position to carry out such tests. Dielectric-loss tests have the disadvantage that they only give the average loss in the length under test, whereas what is required is the maximum loss at any point. Local defects, as, for example, patchy and imperfect impregnation, may escape detection entirely if confined to a small proportion of the total length under test. The ionization test, on the other hand, is difficult to carry out on very high-voltage cables, as it necessitates the carrying out of dielectric-loss tests up to several times the normal working pressure of the cable and the difficulty is self-evident when dealing with cables for working pressures of 66 000 volts and upwards. Evidence of ionization is only too often revealed in a comparatively short time, varying from a few weeks or months after the cable has been put into service. This usually takes the form of free carbon spots, tree-like markings as depicted by the author in Fig. 47, and the

* "Dielectric Hysteresis at Low Frequencies," *Proceedings of the Physical Society of London*, 1912, vol. 24, p. 301.
† *Philosophical Magazine*, 1915, vol. 30, p. 124.

formation of a substance like wax between the layers of paper and usually in the gap between the edges of adjacent paper wrappings. For want of a better practical test it has recently been necessary to seek this evidence by a rule-of-thumb method consisting in applying a pressure of approximately 50 per cent above the normal working pressure to the cable at the works for days and subsequently carrying out a detailed dissection and inspection of a sample of the cable for evidence of ionization such as described. This, it should be noted, is a check test, as it is obviously impracticable to subject every drum or cable to pressure at the works for such a long period. From these remarks it will be evident how urgent is the need for a test which can be easily and quickly carried out on every drum of cable to indicate its suitability for a long life. The rise of power factor with voltage attributed to ionization by Proos and others is a phenomenon well worth further investigation in view of its importance, and more especially in its connection with the previous history of the loading of the cable. I believe this will prove a fundamental characteristic affecting the design of very high-voltage cables. For example, the reinforcement of the lead sheath by armouring will be essential to prevent its expansion, and the use of a fluid impregnating compound and the provision of oil ducts in the cable will ensure that no voids can form on heating and cooling. Opinion is at present divided on this question among the leading manufacturers, but personally I think that a solution of the very high-voltage cable problem will be found along these lines and by employing methods of filling or re-filling or impregnating the cable after it is completely laid in situ. In no other way does it seem possible completely to eliminate the voids formed on bending the cable and the loosening of the lead sheath and of the paper insulation on heating and subsequent cooling. I consider that it will also be necessary to maintain a constant and definite pressure on the oil in the ducts of the cable, as by maintaining a pressure on the insulation in this way the ionization potential can be increased. Further, the pressure of oil ensures that within a limited time during which it may be necessary to operate the cable at a lower voltage the voids themselves become filled with oil. Means are, of course, provided for expansion and contraction of the oil and insulation on heating and cooling. This is readily done by fixing expansion chambers at joints and terminal boxes. These methods are already being tried out by at least two important manufacturers here and abroad with, so far, excellent results. It would be of great value in connection with the ionization theory if the author could indicate whether he has carried out any tests on the constituent parts of high-voltage cables, viz. impregnated paper and impregnating oils or compounds separately, to determine whether the power factor on these varies strictly as the square of the voltage. There is a certain amount of indirect confirmation of this theory in its relation to the previous loading of the cable in the fact that breakdowns of 33 000-volt and higher-voltage cables have been observed to occur in many cases during the night or at week-ends at periods of light load. Section (VIII) of the paper dealing with the time/voltage relationship is of great importance, but I am not prepared to accept *in extenso* the author's general statement that pressure-rises and high-pressure tests may seriously affect the life of the cable. My experience on a very large system of cables up to 20 000 volts for nearly 20 years does not bear this out in the slightest degree, yet, as I have already mentioned, we use reduced thicknesses of dielectric and deliberately insert cables in series with extra-high-pressure overhead lines at terminal points in order to absorb switching surges and protect the substation plant against lightning. These cables must have withstood many hundreds of thousands of such surges and pressure-rises over many years, yet breakdowns of such cables are extremely rare, whilst they fulfil their intended function admirably in a district which, however, is not subject to very frequent or severe lightning storms. I am of opinion that the author's statement can only apply, if at all, to cables of 33 000 volts and upwards, and for these cables I quite agree that frequent and prolonged pressure tests, whether d.c. or a.c., are strongly to be deprecated. Such cables, if not actually operated above the potential gradient which can produce ionization in voids or gaseous films within the insulation at the normal working pressure, certainly incur this condition under pressure tests, with consequent burning and damage of the papers (see Fig. 47). Whether the usual surges or pressure-rises on a large system can produce the same effect even on these cables I am not in a position to say, but I should think it unlikely because of their extremely short duration. Unless, however, the cable insulation can be completely filled and air and gas films thoroughly excluded, the risk cannot be ignored. Dr. Klein * published an interesting series of tests carried out on very similar lines to the author's, which showed that cables which had been overstressed gave reduction of breakdown strength of approximately 10 per cent if broken down immediately, but that if allowed to rest for several weeks before being broken down the breakdown voltage was actually somewhat higher than on cable which had never been previously stressed. He concludes that there is no permanent deterioration, such as ageing, but a kind of fatigue from which the cable can completely recover if allowed to rest. It would doubtless throw some light on this important question if these tests were repeated by applying an intermittent increased stress to a cable operating at normal working pressure to simulate surges, and if, instead of allowing the cable to rest without stress, it were kept under normal working pressure for some hours, days or weeks before breaking it down. I find no difficulty in accepting the tangential-stress theory in 3-core cables referred to in Section (IX), or the pyro-electric theory, or the I^2R theory of dielectric losses. Each and all undoubtedly play their part in the breakdown of cables. Breakdowns on the tangential-stress theory are easily explained, quite apart from the imperfect contact which may exist between the core papers and the wormings on account of the potential difference which exists at the surface of the core insulation between a point on a line joining the centres of the conductors of a 3-core cable and another point on a line joining the centre of each conductor with the centre of the cable. The fact that this by no means negligible

* *Elektrotechnische Zeitschrift*, 1923, vol. 44, p. 233.

potential difference acts in a tangential direction between these two points, accentuates any tendency to burning due to imperfect oil filling, not only between the core papers and the wormings but also between the layers of paper on the core itself in a diminishing degree as the centre of the core insulation is approached. This is in accordance with what occurs in practice where one usually finds burning or charring diminishing from the outside of the core insulation towards the centre on unwrapping, as mentioned by the author on page 121. The difficulty of ensuring perfect contact and oil filling between the core insulation and the centre worming and the different material often used for such wormings, are contributory causes which no doubt accentuate the charring. It is worthy of note, however, that although these two factors also hold for the outside wormings, yet charring is seldom (I think I can say never) encountered on the points of contact with the outer wormings. In considering these theories we must allow for the higher maximum stresses at which high-voltage cables (over 20 000 volts) operate, and recognize that above these voltages we are encountering new conditions. I have never found any burning on 20 000-volt or lower-voltage 3-core cables, and I have no reason to doubt that these cables, if allowed to cool down after prolonged high-voltage tests, do recover and suffer no damage.

Mr. W. T. Maccall: In Fig. 46 is there any particular virtue in the inverse fourth root? That is to say, would not plotting against the inverse fifth root or the inverse cube root give equally reliable values for the breakdown voltage with infinite time? The application of the author's second method (Appendix 1) to the gutta-percha cable (Fig. 11) gives for the 1-, 2- and 4-minute values $I = 0 \cdot 72$ and $n = 0 \cdot 37$; and from the 2-, 4- and 8-minute values, $I = 0 \cdot 69$ and $n = 0 \cdot 33$. It would be interesting to know whether these agree with any values obtained by the slope method, and if so at what times they correspond. I suggest that measurements of the power lost (or of the quantities of charge and discharge) when a cable is charged at a steady pressure and then allowed to discharge would throw light on the probable variation of the component capacities in the model dielectric (Fig 6). In connection with the author's very interesting suggestion of extending his solid models to fill up gaps in our knowledge, it may be worth noting that the power factor is not unity even with a steady pressure, since part of the energy is stored up and is given out again partially on discharge. It may give a better perspective to consider the periodic time rather than the frequency; I do not suggest making the models in this way, since for the scale used for the change from 50 cycles to 25 cycles they would then be some miles long if extended to the steady-pressure cases. What are the author's ideas as to the source of the variation of capacity required by the model dielectric of Fig. 6? In a homogeneous dielectric the resistance of each part $= (1/C) \times$ a constant, if the temperature is the same throughout. Does he consider the resistances to be real resistances, or only equivalent resistances representing the losses in the dielectric due to hysteresis as well as real resistance losses? To use an analogy, the iron losses in a choking coil may be represented by an equivalent resistance; but if the conditions, e.g. frequency, current, etc., are varied this equivalent resistance will change in a different way from the ohmic resistance. I think the case of the dielectric is similar to this, and Dr. Thornton's remarks seem to support this view, but the paper tends to the implication that the resistances are ohmic, and I should like to know the author's opinion on this point. I think that further light would be thrown on this point by comparing the loss tests (or the charging currents) on the same cable (*a*) heated by water, giving sufficient time for the dielectric to reach a uniform temperature; and (*b*) heated by current, but while still on the drum (cf. page 127), so that there is a temperature gradient in the dielectric. This will alter the ohmic resistances of successive layers in different ratios, and so should have a large effect on the losses due to ohmic resistance. Finally, is there any likelihood that the criterion of breakdown in an insulated cable is similar to that for the start of corona on overhead wires? That is to say, does breakdown occur, not when the maximum voltage gradient reaches a certain value, nor, as Fernie suggests, when the minimum stress reaches a certain value, but when the gradient at an intermediate point reaches a certain value, this intermediate point's distance from the core varying with the size of the cable, though not in direct proportion?

Mr. F. H. Williams: From the point of view of the distribution engineer, his requirements in super-tension cables can be stated quite simply. He requires a cable which, once laid, will give no trouble, and he requires a series of tests which he can apply to the cable during manufacture, which tests having successfully been applied he can rest assured that, apart from mechanical damage, the cable will work satisfactorily. When we raised our distribution voltages from 11 000 to 20 000 I do not think that many of us realized that in one step we had actually reached the limit of the particular design of paper-insulated lead-covered cables that we were using, and that future developments could not be met by using the same compound and merely increasing the thickness of dielectric or reducing the potential stress. That, however, was what had happened. The cable maker found that on designing a super-tension cable on the same lines as heretofore the cable tended to heat up when made alive without load, and this heating was traced to losses in the dielectric. To deal with this a different type of impregnating medium had to be sought and a new series of tests discovered. As can be gathered from the paper, the final solution of both of these requirements has still to be obtained, although many miles of three-phase cables for voltages over 20 kV have been laid and are actually in operation to-day. It is a great pity that, the demand having overtaken the development work in the way it has, manufacturers did not realize that they could only deal with an unprecedented situation by heroic measures. One feels that through the Cable Makers' Association or the Electrical Research Association some general pooling of information could have been arranged and a great deal of waste of effort and trouble avoided. Is it too late to hope that something of the kind may still take place? As I have already stated, there are two problems: (1) To manufacture commercially a cable which will operate satis-

factorily at voltages over 20 kV, and (2) to develop a new series of tests to prove that such cables will be satisfactory in operation. The problem of the design of the satisfactory cable is one with which only the cable maker and his research department can deal, but in considering the paper one or two queries naturally arise and I should like to ask the author whether he can show us comparative " V " curves for, say, either a 20-kV cable of the old design or a cable for a higher voltage using the same design and the old type of compound, compared with a cable using the newer type of compound. I should also like to ask him whether he has any data of the losses and behaviour of a Höchstädter 3-core cable. Arising out of the author's theory as to the cause of the " V " curves, has he any data as to the " hydraulic " pressures set up in a cable due either to dielectric loss or to load-current heating when steps have been taken to prevent the expansion of the lead sheath ? The point I have in mind here is that one explanation of the " V " curve, as the author mentions, is that it is partly the result of viscosity, partly the result of expansion and partly the result of ionization. In other words, as the cable warms up the compound becomes less viscous and expands, causing a partial closing of the vacuous spaces, and the dielectric loss falls until ionization of the vacuous spaces takes place, when the curve begins to rise again. A further factor is that there are certain minute air spaces which expand as the cable warms up, and the ionization in these spaces increases and with it the dielectric loss. I think it would be very instructive to plot on one of these " V " curves a curve showing the variation of viscosity with temperatures and the variation of " hydraulic " pressure with temperature. With regard to the testing of super-tension cables I do not like the method approved by the author of heating the cable under test by immersing it in hot water. This gives a heat flow the reverse of that which takes place under ordinary working conditions, and however satisfactory it may be from a research point of view, it is unsatisfactory from the user's point of view as it does not reproduce the conditions of the cable under operating conditions. Further, due to the fact that the lead is hotter than the copper, one would expect the dielectric loss to be increased due to the reduction of the pressure exerted by the lead allowing the formation or enlargement of vacuous spaces. Some tests which I had made with the cable heated (1) externally by water and (2) internally by a circulating current, confirmed this and actually gave, for the cable under consideration, an increased loss of about 50 per cent at 180° F. The difference at a lower temperature was less (as was expected) and was only about 20 per cent. With regard to the testing of super-tension cables, in addition to the standard form of high-pressure test, i.e. " x times normal pressure for 15 minutes," it is customary to measure directly the dielectric loss. Usually this is done while the cable is alive at normal voltage, and in addition to the difficulty of measuring accurately a comparatively small loss practically 90 degrees out of phase with the applied pressure there is the complication of the cable being alive and, usually, of the voltage coil of the wattmeter requiring a resistance which will stand the full voltage. The inspecting engineer responsible for passing such cable is in a very unfortunate position, as he has practically no means of checking the results obtained. There are hardly any published data on the subject; no two manufacturers carry out the tests in exactly the same way with the same apparatus. Further, there is no outside authority to whom he can appeal so as to get the results of various manufacturers reduced to a common basis. It is to be hoped that at an early date the National Physical Laboratory will be in a position to carry out such work and that a method of measuring dielectric losses will be standardized so that the purchasers can make a direct comparison of the results obtained by different makes. As the author points out, however, this dielectric-loss measurement has a distinct limitation in that it only measures the average loss and does not enable us to detect a short, badly-impregnated patch of a cable which has passed the high-pressure tests but will probably cause breakdown in time. A test which will enable faulty impregnation to be detected is an urgent necessity.

Mr. J. Schuil: I should like the author to give his opinion in regard to high-voltage d.c.tests, i.e. whether such tests are detrimental to the cables. Up to about a year ago a steady increase in d.c. cable testing was noticed, but at that time several supply undertakings found that their 33 000-volt cables broke down at the ordinary pressure a few hours or days after the " Delon " test had been carried out. This gave a set-back to d.c. testing for a time, but now with the " Kenotron " method it is forging ahead again. It seems to me that the d.c. test is more piercing than the a.c. test, it penetrates deeper in the insulating layer and therefore finds defeats which sooner or later would have given trouble, and accentuates them. The result will be of great benefit to the industry.

Mr. N. Elkington (*communicated*): The principal fact arising from the paper is how very empirical the manufacture of high-voltage cables is. This is the natural condition of a branch of the industry that has been of financial urgency for only a few years; and I have no doubt that, as usual, there is available among physicists sufficient knowledge, were the facts and needs brought before them, for a scientific explanation of most of the phenomena. There are at least two facts not mentioned by the author that might explain the charring of the dielectric at points where, at first sight, the maximum potential gradient does not occur. In the first place, the dielectric constant is a function of temperature. Hence the incidence of electric force will vary from point to point of the dielectric when the core is heated and the sheath is at a different temperature. I have seen figures for this temperature variation, but cannot recollect where; and I should be pleased if the author would, in his reply, devote a few words to the subject and give any reference he may have seen. In the second place, the actual charring of the paper is due to oxidation of, or similar chemical action on, the less inert constituents. So that if a cable were about to break down along the heated path of an ohmic leak the charring would not necessarily occur at the point of maximum electric stress, or even of maximum temperature, but at the point of most conductive gas. Besides

considering entrapped air in this connection, it would be interesting to know what gases would be liberated from the impregnating fluid into the vacuous space occasioned by the separating of layers of paper during the handling of the cable.

Mr. L. C. Grant (*communicated*) : The author appears to be of the opinion that ionization in the dielectric and relatively high-frequency surging account for many of our cable troubles. If the design of the dielectric is right, ionization is usually due to non-uniformity, and entrapped air is often blamed for troubles of this nature. Inspection of extra-high-tension cable faults appears in many ways to confirm this view and much good could, no doubt, be done by improved methods of wrapping and impregnation so that air and impurities in the oil and paper are excluded. Manufacturers are working on these lines and are probably best competent to deal with this aspect of the problem. Cable troubles at 10 000 volts working pressure will come as a surprise to many of us, but the fact that the troubles were eliminated by the use of surge-absorbing appliances is none the less interesting. The method of handling surges is important, and it is difficult to see how any apparatus employing resistance or spark-gaps alone or in combination can be effective. Spark-gap and resistance devices work by connecting the affected line to earth and thus reducing the potential, but it is possible to prove by simple mathematics that effective protection cannot be obtained in this manner. To be effective, the resistance must prevent the oscillations building up and to achieve this the resistance should be at least twice the surge impedance of the line. Greater values of resistance are usually employed. With such an arrangement it is possible to limit the extent of a pressure-rise, but it is not possible to prevent some rise taking place. To put it briefly, there are two limits : On the one hand the resistance must be kept high to prevent oscillations building up, but on the other hand it must be low enough to prevent a dangerous voltage-rise. Normally, resistances used in this way are capable only of limiting the voltage-rise to something like 70–80 per cent of the maximum possible value. Spark-gap devices are of doubtful value, first because they must be set at some voltage above the line voltage before they will operate, and, secondly, because a spark-gap tends to promote oscillations on its own account in much the same way as in Tesla and wireless apparatus. To overcome these troubles the surge-dissipating device should be of a non-oscillatory form and should contain no spark-gaps. The "Campos" device and the surge-absorber described by Captain Ferranti at the Paris Conference operate by dissipating the energy of the surge in the form of heat. In the "Campos" arrangement, inductance shunted by resistance is employed to localize the pressure-rise and to dissipate it in the form of heat. One of the objections to this arrangement is that it is difficult to build and insulate a resistance capable of handling sufficient energy to give efficient protection. The other arrangement overcomes this trouble by utilizing a step-down effect so that the dissipator is able to handle large amounts of energy, whilst the insulation required is of an ordinary character. Condenser devices and inductance coils, no matter of what form, are alone quite incapable of dissipating the surge energy : in fact, they tend to set up and maintain surges. Properly embodied, however, their characteristics can be usefully employed in surge dissipators where they have a definite duty to perform, but that duty can never be the actual dissipation of the energy in a surge.

Mr. E. B. Nixon (*communicated*) : What is the author's opinion of graded dielectrics for super-pressure cables ? Such dielectrics would appear to solve the troubles at present experienced with impregnated paper. This point is linked up with the requirements of many speakers in the discussion, i.e. new methods of testing to localize incipient cable faults. The suggestion is made that graded dielectrics would nullify this demand. It should be possible to give, within reasonable limits, the testing voltage a cable will withstand, and also the puncture voltage. These tests would be carried out on test-lengths only, and the final test on the cable when laid would be a d.c. test of a voltage suitable to prove that the laying and connecting have been well done. From the testing voltage can be derived the safety factor, if this is desired, i.e. safety factor = (testing voltage for a period of, say, 1 hour)/(line pressure). I think that the author will agree with these principles, for there is no doubt that, as he states on page 121, high-voltage tests may damage the insulation, and after all they do not prove that the cable will be satisfactory.

[The author's reply to this discussion will be found on page 144.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 17 NOVEMBER, 1925.

Mr. C. J. Beaver : Like the majority of papers which deal with electric cables, this paper is chiefly concerned with the electrical aspect of the subject ; it usually seems to happen that very little account is taken of the physical or chemical aspects, and one is rather liable to lose the proper perspective of the whole thing. There is perhaps too much inclination to deal with the subject on a mathematical basis, and to ignore factors which are not susceptible to mathematical treatment, such as the heterogeneous structure of the material and its chemical stability or instability. There is much in this paper which is known in a general way but, like a lot of those things which we think we know, a great deal more reveals itself when we come to look thoroughly into the subject and analyse it completely. For example, the electrification and the time/voltage relationship to which the author has referred is an everyday matter to those who have to test electric cables in the factory. Variations of it in analysing anything suspicious are used as almost a matter of everyday occurrence. Taking a general survey of the paper, the author seems to have vacillated somewhat before reaching his I^2R loss conception, and to have accepted as the whole story what most authorities on

the subject agree is a substantial part. We have to remember that, whatever conception we may have of it, it all comes down to a common end. The penultimate stage results in the dielectric becoming more or less conductive, and the ultimate breakdown is simply a matter of sufficient energy per unit volume of the dielectric being liberated in it, after that state has been reached. In other words, this common end of the mechanism of breakdown—whatever the intermediate processes may be—is accountable for by what the author has referred to as the pyro-electric theory. The claims for his theory, as stated on page 122 under six headings, refer to points which really have been quite convincingly explained by other theories—such as the ionization theory—although the points do not strictly come into line. To take the first—"the presence of the charred patches in isolated places after prolonged test"—I think, for the reasons I have just stated, that this cannot be claimed to support the I^2R loss theory. It is a pyro-electric effect. The second one—"the peculiar designs assumed by the charring"—is much more characteristic of ionization in air or gas spaces than of simple charring effects. They are the sort of tree-formation appearances which one would associate with static discharge, the charring or burning being an advanced stage of it. Next, the time/voltage relationship and the overloading to which the author refers seem to me to amount to this, that when we either overload the cable or overstress it we do something which leads to a disturbance of the physical state of the chemical composition, and we cannot expect to get the same result after we have set up the incipient conditions for the process of breakdown. The shape of the burnt-out path through the dielectric is simply determined by the path which we have more or less rendered conductive. It may be radial in direction, or curved or angular in relation to the axis of the cable, according to the imperfections or impurities which have determined the path in the earlier stages of its development. The author's last point—"the difficulty in employing the logarithmic formula connecting dielectric stress, dimensions and breakdown voltage"—has, I think, no relation to his claims. The difficulty has been very thoroughly discussed by various writers, and one need only look at it from this point of view, that these theoretical formulæ assume an isotropic or, at least, homogeneous dielectric which does not exist in actual practice. The kind and degree of heterogeneity vary in different dielectrics. For example, a varnished-cambric cable dielectric is very coarsely heterogeneous, consisting of cellular parts composed of woven fabric interspaced with varnish films. Further, the cellular parts cannot be perfectly freed from air and moisture, so that the mass as a whole is far removed from homogeneity. Yet this type of dielectric is often referred to in accounts of experiments bearing on the proof of theoretical formulæ. The author's reference to the intersheath form of cable is rather interesting to me because I was, in 1914, the apostle of intersheath cables; and the interesting part is that the author says exactly the opposite to what all my critics said in 1914. They said that if there were any weaknesses in the layers of dielectric the intersheaths would line them up and the cable would break down; whereas the author says that the intersheaths will, according to his I^2R theory, strengthen the dielectric simply by their presence. On page 120 the author has referred to a matter of extreme importance regarding the protection of high-voltage cables in use. I know that there will be a lot of disagreement as to the necessity of it, but the article by Mr. Partridge of the London Electric Supply Corporation referred to in Appendix II (36) showed some very remarkable and significant results. The subject is worthy of very close attention and should not be lightly dismissed. There is a good deal more in it than the author's brief reference indicates, and I recommend its careful perusal. The author's reference on page 122 to statements I have made regarding losses in paddings or wormings in 3-core cables relates, I take it, to a lantern slide which I showed here about 9 months ago; and as unimpregnated wormings were not referred to, and, further, as the bearing of the whole matter had

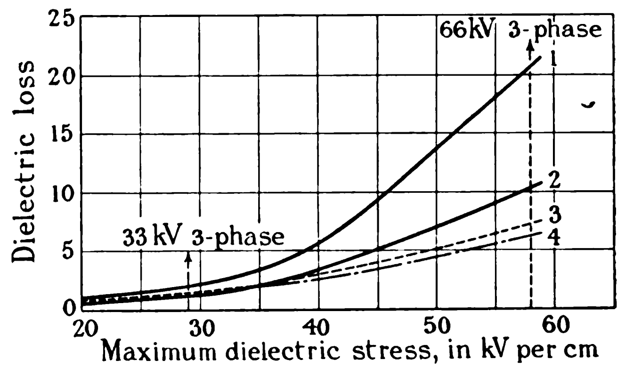


FIG. H.—Comparison of types of padding. Variation of dielectric loss with dielectric stress. Tests at air temperature.

Cable 1.—Cable with ordinary impregnated paper padding.
Cable 2.—As Cable 1, but padding filled with compound under pressure.
Cable 3.—Cores as Cable 1, but padding of homogeneous non-fibrous material.
Cable 4.—Theoretical curve for Cable 3, assuming constant power factor.

reference to the elimination of air from padding spaces and its effect on losses which were clearly due to ionization, I should like to show the slide again. According to my notes, I quoted a statement by Mr. Tracey of Messrs. Johnson and Phillips, at an Informal Discussion in London on the wattmeter method of measuring dielectric losses, to the effect that if the losses in a multicore cable could be segregated and analysed, 75 per cent of them would be found to occur in the filler spaces. I showed the slide in question (Fig. H) to illustrate my experimental confirmation of what Mr. Tracey had predicted. The loss/stress curves in Fig. H relate to three cables, the cores of which are identical. In the first case the cores were laid up with ordinary impregnated-paper padding. The second cable was identical with the first, but the padding was filled with compound under pressure. In the third cable the padding was made of a homogeneous non-fibrous air-free material. It will be seen that the losses are of the same general order in all three cables at stresses between 20 and 30 kV per cm, but there is a very considerable difference between them at stresses

of the order of 50 to 60 kV per cm, i.e. at stresses at which ionization in air spaces can freely occur. Comparing curves 1 and 2 at 60 kV per cm, it will be seen that in the latter curve the total losses under three-phase test conditions have been reduced by 50 per cent, as the result of filling the impregnated paper padding with the compound under pressure in situ, whilst the substitution of the ordinary impregnated paper padding by the homogeneous air-free material

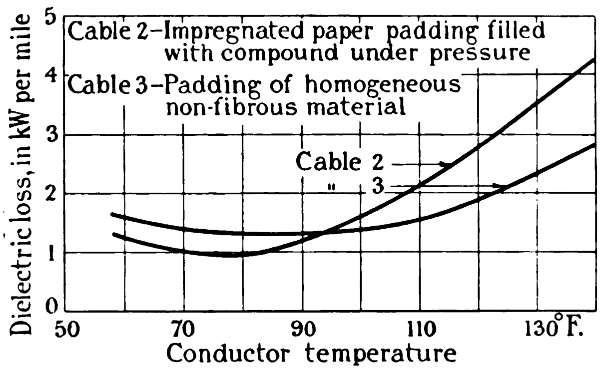


FIG. J.—Comparison of types of padding. Variation of dielectric loss with conductor temperature.

reduces the losses by 60 to 70 per cent. The theoretical curve (4), plotted on the assumption of constant power factor, lies very close to curve 3, showing the very marked effect of eliminating occluded air and gases from the padding spaces. This does not, however, necessarily reduce the power factor. It is well known that at stresses below those at which ionization occurs

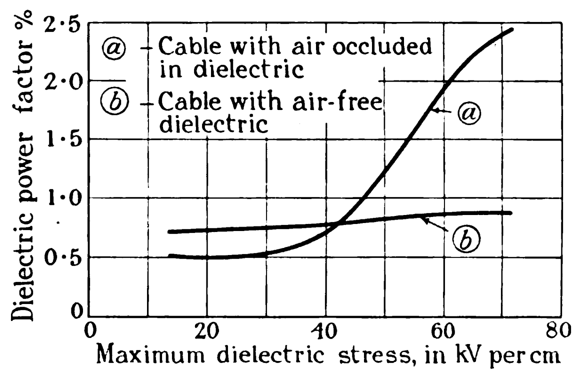


FIG. K.—Variation of dielectric power factor with dielectric stress. Test on single-core cables.

a dielectric containing appreciable proportions of air may have a lower power factor than an air-free dielectric. Fig. J shows the loss/temperature curves for cables 2 and 3, from which it will be seen that, owing to the different shapes of the curves, the values over the lower portion of the temperature range are lower for cable 2, containing air in the padding spaces, than for cable 3, containing practically none. The point is further illustrated in Fig. K, which shows the power-factor/stress characteristics of two single-core cables of similar dimensions, cable (*a*) containing air and (*b*) being free from air. It will be seen that (*b*) has a higher power factor than (*a*), but the power factor remains approximately constant over the whole range of dielectric stress, whilst (*a*), as a result of containing air, shows a fairly rapid increase in power factor at stresses exceeding that at which ionization commences. It will be clear that all this evidence is more in accord with the ionization theory than with the author's I^2R theory. A further point in this connection is that the partially solidified impregnating material which is frequently found in conjunction with the charred tree-like formations in an overstressed dielectric has been proved to be an oxidation product, which clearly indicates the presence of air. In conclusion I should like to refer to one or two of the author's statements regarding the hypothetical fault illustrated in Fig. 51. I consider he is not entitled to say that an effect which he finds to occur on the surface of freely exposed impregnated paper will also occur in the interior of a cable dielectric. So far as dispersal of compound around the test-electrodes is concerned, the phenomenon is quite familiar. I have always attributed it to electrostatic repulsion between free particles of material. Similar conditions do not exist inside a cable dielectric, except in an actual cavity, and although the presumed travel of compound is not inconceivable I have never found any evidence of it in practice.

Mr. H. Hawkins: I intend to confine my remarks more particularly to the question of design, because I feel sure that the selection of a suitable design would carry with it the solution of some of the problems which the author has described. From my experiences of 33 000-volt three-phase cables I have become a convert to Höchstädter—to his type of cable and to his theories—and I suggest that his cable, or one of a fundamentally similar type, would provide a solution of many of our difficulties. The Höchstädter cable differs essentially from the type of cable under consideration in the paper, i.e. the standard 33 000-volt cable in use to-day. In the Höchstädter cable the belt or girdle of insulation encircling the grouped cores is absent, a proportionate amount being added to the insulation of each individual core; and each of the three cores has finally its own copper sheath in contact with the lead sheathing. From my experience I should perhaps feel inclined to add to such a cable a brass, or copper, constricting band encircling the three cores, as it would keep the core sheathings in intimate contact throughout the life of the cable and would also tend to localize the effects of faults. Incidentally, it may be presumed that such a cable would be less liable to faults between phases than one of the "belted type." I am aware that such a constricting band was used on a beltless super-tension cable which has, I understand, been in successful operation at 55 kV for some years, and in that cable the band has a more essential duty to perform. The author would appear to support me in my contention that such a cable merits attention. I refer to his article (No. 31 in Appendix II) in the *Electrician*, where he alludes to a three-phase cable made by his company. He states that such a cable, known as the "S.L. type" (which if not of the exact Höchstädter pattern is at least beltless, when used for pressures above 33 kV), offers

"enormous advantages." This statement brings me back to Höchstädter's theory of "limiting voltages," governed by the fact, he affirms, that above approximately 15 000 volts to earth and 25 000 volts between phases the quadratic law of dielectric loss is no longer true for three-phase cables (of the belted type), and the loss is proportional to higher powers. I would, however, supplement this by a further quotation from the author's article previously referred to: "Where pressures exceeding 22 kV are under consideration quite a new range of phenomena enter into cable manufacture and operation." Now, if I accept this theory of "limiting pressures," I am driven to the conclusion that there should logically be but one type of three-phase cable for all pressures above 22 kV and that one the Höchstädter, or one of the allied beltless types, which should offer some if not all of the advantages claimed for the original. The chief of these advantages is perhaps the elimination of those "annoying tangential stresses," owing to the fact that the whole of the outer surface of the dielectric of each core is kept at earth potential by its metallic sheathing, inside which there is uniform stress in every direction. If such a standard type, as I suggest, had already been in existence and generally adopted, the somewhat anomalous position in which users of 33-kV three-phase cables at the present time appear to be would have been avoided, as we are now told that other types offer "enormous advantages" for pressures above 33 kV, which leaves us in this dilemma. Are we to lower our working pressure below 22 kV in order to escape from the implied disadvantages under which we suffer, or are we to change the type of cable and raise our voltage? If it is not denied that improved types of cable are capable of giving satisfactory service at pressures of 44 kV and above, it must surely be agreed that such a type if used at 33 kV would at least give a greater "factor of safety," and, further, that its users could, without excessive increase in their original outlay, have the opportunity, which they have not hitherto enjoyed, of being able to raise their working pressure at some future date. I feel that perhaps I owe the author an apology for the above remarks, inasmuch as they may not be accepted as strictly germane to the points at issue, but I consider that a fundamental alteration in the present type of cable would offer a solution of many of the problems mentioned in the paper. In conclusion I would ask the author, placing his own valuation on the great advantages of the type of cable he has advocated for pressures above 33 kV, would not the improved "factor of safety," if such cable were used at a lower pressure, relieve users of some of their anxieties in regard to the phenomena mentioned in the paper, and further, would it not provide an answer to some of the questions which require settling as between maker and user?

Mr. H. M. Crellin: I do not agree with the author's I^2R theory as an explanation of either dielectric absorption or alternating-current losses, or as the primary cause of dielectric breakdown. With regard to Figs. 4 and 6, I think that it is quite legitimate, for the purpose of mathematical analysis or to facilitate calculation, to represent an absorption condenser as equivalent to a combination of a pure (or no-loss) condenser shunted by a resistance, but I am quite convinced that such an arrangement does not represent the true physical action in an absorptive condenser. Consider the application of a d.c. voltage across the condensers and resistances shown in Figs. 4 and 6, e.g. when connected across a battery. If now the connection between the condensers and the battery be broken those condensers would all be immediately discharged through the resistances in parallel with them. This does not happen, however, in an actual cable. Even if one endeavours to conceive the values of the resistances to be so high as to allow the condensers to discharge extremely slowly, the resistances would have too high a value to carry the comparatively instantaneous and large current necessary for the absorption component. Take another instance bearing on the same point. In Fig. 24 the dielectric loss for a 30-yard length of 0·1 sq. inch cable is given as roughly 0·002 watt at, say, 100 volts. This figure corresponds to an "effective" or, shall we say, equivalent (mathematically) resistance of 5 megohms for that length, or 0·085 megohm per mile of cable. I cannot accept this figure as representing a real physical resistance, because a condenser shunted by such a low resistance would not hold (as a real cable will) the charge from a low-voltage battery when testing the electrostatic capacity by the direct-deflection method. From pages 121 and 122 the author's contention, apparently, is that all breakdowns are preceded by some charring through heating caused by displacement currents. In my opinion this is incorrect. I cannot conceive that in the case of a cable or other dielectric subjected suddenly to a pressure so much above its breakdown strength as to cause instantaneous rupture that the breakdown is preceded, or caused, by charring due to displacement currents. I agree that on tests with pressures lower than the instantaneous breakdown values, applied for comparatively long periods on cables or dielectrics containing defects, some charring due to internal discharges across such defects may precede and accelerate breakdown, but such action does not to my mind represent the true physical nature of breakdown under electric stress any more than would a theory that the invariable cause of failure of metals under tensile or compressive stress is entirely due to defects in the metal.

Mr. A. Philip: On page 121 the author states that "paper fibres . . . no doubt have tiny quantities of moisture," and I should therefore like to have his opinion as to the extent to which moisture is allowable in cable paper. We find that in the paper of most high-tension cables which we have examined moisture is present to the extent of from 1 to 2 per cent, and I should like to know if the author considers these values to be excessive. In my opinion the absorption equation $I_t = I + At^{-n}$ is not at all satisfactory, because (1) it is based on a study of gutta-percha cables and thereafter applied to paper cables, and (2) the so-called constants are really variable. It is not quite clear from the paper whether Granier actually uses this equation in his treatment of the subject, and I should like to know if the author has calculated the a.c. losses from Granier's expression and the index n for any

particular cable for low voltages where the question of ionization does not arise. The absorption curves given in the paper commence usually at a value $t = \frac{1}{4}$ minute or $t = 1$ minute, whereas under a.c. conditions the times involved are very small fractions of a second, so that it is difficult to connect the d.c. index n with Granier's n. It would also be interesting to know how the absorption equation "constants" vary with the voltage.

Mr. B. G. Churcher: The need for a theory connecting d.c. with a.c. dielectric phenomena has long been realized and I think the present paper is a valuable one in that direction. It has long been known that the a.c. losses are not generally merely a matter of simple conduction. That is to say, the loss is not equal to E^2/R, where E is the applied P.D. and R the insulation resistance measured with direct current. However, there is actually one case where the a.c. loss is equal to E^2/R. This occurs in very poor-class insulating materials, such as slate, in which a power factor of unity may be obtained. These materials behave like conductors. The resistance is invariable with the frequency and the d.c. resistance is equal to the a.c. resistance. Another speaker has already raised a question in regard to the curve connecting the absorption index with the power factor (Fig. 22). I should like to know whether the author has taken a cable, measured the capacity of the cable with direct current and from the absorption index calculated the power factor; then for a given a.c. voltage and frequency applied to the same cable has calculated what the dielectric loss should be, checking the value so obtained by a wattmeter measurement. That would seem to be a crucial test of the theory. I should imagine that the different values of n at different times during the charging period would make it difficult to get an accurate check. The deduction on page 109 regarding the variation of power factor with frequency is interesting. I have looked up the ratios of the power factors at 25 and 50 cycles for two materials. In a sample of rather low-grade bakelite with a power factor of 0·17 the ratio was found to be 1·22, and for ebonite with a power factor of 0·016 the ratio was 1·05. These values tend to confirm the author's deduction. In connection with the theory of parallel condensers and resistances, it is perhaps rather necessary to point out that although we may make a sort of model the performance of which fits the observed behaviour of the dielectric very well, it cannot be argued that because the transformation of electrical energy into heat energy takes place according to the I^2R law in the model, that therefore the same thing happens in a cable. Models of that kind, or equivalent circuits, can be made to represent many electrical phenomena, but they do not indicate what is actually happening inside the apparatus which the model represents. I do not wish in any way to depreciate the value of the model for purposes of calculation, but I think it is necessary to bear in mind this limitation. With regard to the "V" curves given on pages 110 and 111, I have not, on any materials of which I have had experience, found the power factor to decrease with an increase in temperature in the region of 20° to 30° or 40° C. I am speaking, of course, of materials which are used in the insulation of electrical machinery and not in cables. These materials give a roughly constant power factor from about 20° to 30° C., after which the power factor increases. I should like to know whether the "V" curve is a peculiarity of the materials used in cables or whether it arises from the way in which the insulation is applied in the manufacture of a cable. The figures in Table 5 showing the relation between the d.c. and a.c. losses are very interesting. Although the power factors are not given, the tests were made, of course, under conditions of increasing power factor, as the power factor increases in general with temperature. It is shown that the ratio of d.c. to a.c. losses comes nearer to unity as the temperature is increased. I take it that if one could heat the cable sufficiently without damaging it, unity power factor would be reached and the d.c. loss would be equal to the a.c. loss. With regard to the effect of stress on power factor, has the author considered the rise of the average temperature of the dielectric in a cable, due to dielectric loss? Taking some figures given in the paper, I have worked out a case where one can get quite an appreciable temperature-rise for a voltage of 70 kV and a thickness of insulation of 1 cm. For instance, taking the permittivity of the insulation as 4, the thermal resistivity for oil-soaked paper as 250, and the frequency as 50; then taking the curve in Fig. 25 the power factor at 50° C. is 0·02, which gives a loss of about 0·011 watt per cm^3. Assuming that the testing voltage were kept on for a sufficient time for thermal equilibrium to be attained, the dielectric loss would give an excess of temperature on the inside of the insulation over that on the outside of about 1·4 degrees. If the cable is heated up to 70° C. the curve shows that the power factor will be about 0·09, which will give 0·048 watt per cm^3, and a temperature difference between the inside and outside of the insulation of about 7 degrees. Looking at the power-factor curve, it can be seen that at 70° C. the curve is very steep and an increase of 2 to 3 degrees in the average temperature of the insulation would increase the apparent power factor quite appreciably. Of course there is little doubt that a great deal of the increase in power factor with stress, observed by the author, is due to discharge across air inclusions, but I should like to ask him whether he thinks that the increase of power factor due to heating by dielectric loss is negligible. In testing specimens of material where there is little or no chance of air inclusions one usually assumes that an increase of power factor with stress is due to internal heating. The magnitude of the effect is usually consistent with this view.

Mr. E. L. Davey: Maxwell explained d.c. absorption and residual charge on the basis of a heterogeneous dielectric, and the author has endeavoured to apply this to a.c. conditions, explaining the a.c. losses as being due to the absorbed charge currents flowing through resistances and discarding the idea of a dielectric hysteresis. It is interesting to note that Del

Mar and Hanson * showed that the effect of the composite structure of insulation was to increase the loss under a.c. conditions due to the fact that the voltage was capacity distributed, whilst under d.c. conditions this distribution was in proportion to the resistances and a minimum energy loss was involved. This conception is much clearer than that of a current flowing through a resistance to supply an internal or absorbed charge, since it is difficult to visualize an absorbed charge under a.c. conditions. Del Mar and Hanson stated that the increasing of the loss would be independent of frequency, i.e. the behaviour of the loss of a composite dielectric would be governed by the behaviour of the losses in the materials used in building up the dielectric. The dielectric hysteresis idea has a physical basis and is appreciated by virtue of this, whereas the conception presented by the author has no such basis. The hypothesis of a condenser and series resistance for a dielectric under a.c. conditions at low temperatures is quite unsatisfactory for several reasons. In the first place the dielectric power factor at low temperatures is independent of the frequency, whilst that of the condenser arrangement is governed by the relation $\cos\,\theta = \omega CR/\sqrt{(\omega^2C^2R^2 + 1)}$ into which the frequency enters appreciably unless R is very large. The approach of independence of $\cos\theta$ with respect to frequency is simultaneous with $\cos\theta$ approaching unity, and this is not in accord with the low values of power factor met with in practice. For a reasonable value of power factor we must have a very low value of series resistance, but this is contrary to the values of resistance met in connection with dielectric work, and also under these conditions $\cos\theta$ approximates to a value ωCR, i.e. it is dependent upon the frequency. In the I^2R explanation of the "V" curve of dielectric loss it becomes necessary to revert from the series arrangement of resistance to a parallel arrangement. This is purely a mathematical artifice and can by no means be called an explanation of the "V" curve, a true explanation of which connects up the electrical behaviour with the physical changes that take place as a result of the heating. Höchstädter and Pungs have pointed out the great similarity between the behaviour of the a.c. losses of the impregnating compound and the losses in the actual cable with respect to frequency and temperature. The close coincidence of the minimum-loss point with the melting point of the impregnating compound also merits great attention, whilst the work of the physicists such as Decombre, Jaffé, Malclès, etc., on ionic motion in dielectrics cannot be lightly passed over. As a result of the Granier relationship betwen the a.c. power factor and the d.c. absorption index n, the author states that so far as absorption losses are concerned the perfect cable dielectric is one which in the index n equals unity, giving zero power factor and hence no absorption losses. This is not in agreement with the equation $I_t = I + At^{-n}$, where At^{-n} represents the current supplying the absorbed charge, since the latter is not zero when n equals unity but only when A equals zero, as can be shown by a study of the absorptive condenser of Fig. 4. The value of the index n for a paper-insulated cable falls from about unity to 0·5 as the temperature is raised from 10° C. to, say, 60° C., and according to the Granier formula the power factor should rise with increase of temperature to an extremely large value, such as is never met with in practice. Also, until n equals zero the loss depends upon the frequency to some extent, but in practice it is independent of the frequency for temperatures above 50° C. No explanation of the minimum-loss point can be given on the basis of absorption since, as shown above, the absorption losses increase steadily with temperature. In connection with the tests on celluloid conditioned at various humidities, it is interesting to note that Du Bois gave an explanation of dielectric loss based on the mechanical action of moisture in a dielectric field and supported his theory by experimental results on a cable which had been given less drying than usual. Marbury has also recently shown that the effect of moisture is greatly to increase the d.c. absorbed charge, but with well-dried cables this effect should be negligible. It is stated from a consideration of Fig. 34 that it is evident that by far the greater part of the losses round 80° C. are cyclical, but judging by the 150° F. line of Fig. 36 this would not seem to be the case since the loss is independent of the frequency from about 5 cycles per second upwards. The capacity voltage-distribution theory will give a very reasonable explanation of this. This point also illustrates the drawback of endeavouring to connect up the d.c. losses with a.c. losses at 25 and 50 cycles. At very low frequencies the loss curve rises suddenly with respect to frequency and no explanation of this can be advanced on the basis of the I^2R theory. The author's explanation of the minimum-loss point refutes his main theory, as he states on page 114 that the absorption losses seem to have in them two components to produce the dipping curve. We only have to specify that the decreasing component varies as the frequency, and we have arrived at the Höchstädter explanation. The effect upon its ionization characteristic of heating and cooling a cable is well known and can be explained by the action of the draining of the impregnating compound and also the lowering of the pressure of the entrapped air due to the compound solidifying under pressure. Thus curve A in Fig. 39 represents a cable having occluded air present in the dielectric, this air being uniformly distributed, and curve C represents a much less uniform state. As would be expected, this effect is practically absent in a thoroughly impregnated dielectric. Owen's method of plotting breakdown voltage against the inverse fourth root of time has been used in a very arbitrary manner, and the conclusion that a cable would support indefinitely voltages below a certain value is unwarranted. The maximum time taken in the breakdown tests is of the order of 60 hours, and the author has assumed that the straight line variation of breakdown voltage with the inverse fourth root of time holds for time values of the order of a number of years, irrespective of the variation of the rate of deterioration of a cable with time. The outcome of the study of the nature of cable breakdown seems to suggest that the utmost

* *Transactions of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 563.

care should be taken thoroughly to impregnate a cable dielectric and to exclude air. The I^2R theory does not explain the increase of dielectric loss at low voltages with better impregnation of the dielectric. This experimental fact supports the ionization theory, as air has practically no loss when stressed electrically until it becomes ionized, and then the loss increases at a very rapid rate. The author's explanation of the motion of the impregnating compound near a weak patch in a cable dielectric is opposed to a fundamental law of the dielectric circuit, namely that a material of high specific inductive capacity is urged towards the strongest part of the field from weaker parts until a maximum amount of energy is being stored in the dielectric field. Steinmetz and Hayden based their breakdown theory of liquid dielectrics upon this law and it can be illustrated experimentally by dropping water, etc., into an oil gap. Clark and Shanklin are referred to as having given an explanation of the " V " curve on the ionization basis, but in their actual tests in 1917 they found that the dielectric loss for all their cables increased steadily with temperature throughout the temperature range. If the stress is high enough and air is occluded within a dielectric the " V " curve is made more prominent due to the losses being increased by the ionization losses at low temperatures, whilst at high temperatures the pressure of the occluded air is sufficiently high to prevent ionization. The heating of a cable for dielectric-loss tests by placing it in water has the drawback that the whole of the dielectric is at a uniform temperature and the effects of the temperature gradient on the dielectric loss are missed.

Mr. J. L. Carr: The phenomenon of dielectric absorption has been explained by an arrangement of condensers in cascade, with resistances in parallel, and I think that this theory received support from Steinmetz himself some two years ago. In my opinion it seems to provide a reasonable explanation of what occurs in charging and discharging an electric cable. I am rather disappointed that the author has devoted so little space to the question of the design of, and the development of breakdown in, electric cables. These considerations would, I think, be of greater interest to the majority of electrical engineers at this time than the question of dielectric absorption. In this connection there are one or two points which I should like to raise. On page 121 there is a statement attributed to Fernie, that the breakdown of a high-voltage cable takes place at the point of minimum stress. To my mind this is an absurdity. A chain is no stronger than its weakest link, and it is not reasonable to assume that a cable will break down at the point of least stress. It is a fact, however, that cables do break down at a point adjacent to the position of minimum stress calculated according to the logarithmic formula, but this is largely due to the fact that the stresses in a 3-core cable are not uniform; and, quite apart from the tangential stress described by Höchstädter, there are other stresses which lie along the individual layers of paper rather than across them, and, given certain other conditions, this results in a discharge taking place at this point. In this connection, it is a matter of easy verification that in the presence of air and moisture it is comparatively much easier to produce a flash over the surface of an insulating material than to puncture it. In the case of paper impregnated with cable compound, a flash-over in the presence of air and moisture takes place very easily. I am speaking of cables subjected to a pressure far beyond that at which the cable is intended to work, provided that the insulation is sufficiently good, and the cable well impregnated, without considerable air spaces. During these tests, discharges become apparent after a time, and if in the early stages the interior of the cable be examined, the effect of the discharge is seen to lie in the compound on the surface of the paper without actually damaging the fibres, so far as can be seen under the microscope. If the test be extended over a considerable period, the paper itself becomes charred. This, I think, rather supports the view that the initial discharge which occurs on the surface of the paper is due to the presence of air or moisture. As soon as a discharge takes place, the presence of carbonaceous matter in the cable itself tends still further to disturb the stresses and produce still greater discharge. As far as my experience goes in carrying out tests on short lengths of single-core cable, in the majority of cases the cable shows signs of breakdown first at, or near, the point of calculated maximum stress, that is, near the conductor, although it is fairly easy to understand that there may possibly be signs of discharge at other points.

[**Mr. H. A. Ratcliff** also took part in this discussion. The substance of his remarks will be found on page 127 in connection with the discussion before the Institution.]

The Author's Reply to the Discussions at London, Newcastle and Manchester.

Mr. P. Dunsheath (*in reply*): In presenting the paper I expressed a hope that, whether or not the paper itself added to our common stock of knowledge, at least good would come from the subsequent discussion. The wide field covered by the many valuable contributions to the discussion, and the kind appreciatory comments on my ideas by acknowledged authorities, make me feel that in both respects the paper has been worth while.

In connection with the relationship between d.c. conduction and a.c. loss in a cable at its higher temperature, Mr. Melsom refers to the important investigations of Mr. Evershed, but I have carefully studied Mr. Evershed's paper and can find nothing that carries us very far in this matter. The most useful prior publications are those of Dr. Fleming and Mr. Dyke, and Mr. Addenbrooke, referred to in the paper. I fully agree with Mr. Melsom that the Section on assessment of cable quality could be amplified with advantage, and perhaps one day we may have an Institution paper on the subject. It is worth an entire paper to itself. As Mr. Melsom does not say in what respect he dis-

agrees with what I have said in this Section, it is not possible to reply very usefully.

Mr. Emanueli's support of my experimental results demonstrating the existence of the "V" curve at low voltage is very gratifying, but he brings out a new and valuable fact in showing the existence of a maximum point at about 0° C. I have not carried out tests at these low temperatures, and without further investigation it is difficult to explain with certainty this maximum point. The value of the temperature at which it occurs, however, suggests some connection with the freezing of moisture particles or filaments. Although I had not thought of it before seeing Mr. Emanueli's curves, the results are consistent with the theory of the "V" curve which I have advanced at the bottom of page 109, col. 1. As the temperature falls the values of the series resistances may only continue to rise down to the freezing-point of water, and if at this point the negative temperature coefficient disappears, as is quite probable, the falling part of the "V" characteristic will reach a limit here and the curves will be explained. The nature of the variation of power factor at the higher temperatures in Mr. Emanueli's Fig. A is consistent with that shown in my Fig. 43, but I cannot understand the increase with frequency in his tests between 0° and 20° C. The shifting of the minimum point by alteration of compound, referred to by the same speaker, is also illustrated in my Fig. 41, and I can confirm his statement that the addition of rosin moves the point to the right. With the rest of Mr. Emanueli's remarks on the various questions of inspection of cables, undesirable reductions of dielectric losses, methods of heating cables for loss tests, etc., I am in entire agreement.

Mr. Ratcliff questions the application of the well-proved time-voltage relationship to explain the breakdown of cables months after installation. If he accepts the nature of the curve—and there is sufficient evidence to make this necessary—then I cannot see why he should decline to accept the application. He also raises the vexed question of factor of safety, and bases his requirements on a 25-year life. If, now, we could determine the 15-minute test voltage which is equivalent to 25 years at the working voltage, it would be necessary to obtain only a small percentage increase on the test value in order to extend the life of the cable by a second 25 years, presuming, of course, identical conditions in both cases. The reason for this is that after a long time the time/voltage curve is very nearly flat and a slight change in the height is accompanied by an enormous change in the time. The really important fact that we must face is that different dielectrics and, therefore, different cables have different time-voltage curves, and the fact that two cables have the same factor of safety on a short-time test is no criterion that they will have the same factor of safety over years of service. Mr. Ratcliff's remarks as a cable user on the desirability of installing protective gear are of considerable interest, although in the light of the results obtained by another cable user quoted in the paper, and of views expressed by other members in the discussion, for example, Mr. Beaver and Mr. Grant, it does not appear that the last word has been said on the subject. He expresses the opinion that the cables themselves are the most effective absorbers of transient high-frequency disturbance on a system, but we must bear in mind that this is not the prime function of a cable, nor are cables designed with a view to make them efficient shock absorbers. I think it must be admitted that if a system is subject to pressure-rises and the engineer does not wish, for various reasons, to install protective devices, then the cable must be designed more generously than if all precautions were taken to prevent the voltage exceeding the normal working value. I am in agreement with Mr. Ratcliff on the relative reliability of three-core and single-core cables, and I refer to the matter below in replying to the points raised by Mr. Hawkins.

I see that Mr. Ratcliff and I are not in agreement over the method of heating a length of cable for dielectric-loss tests. He claims that where a cable is heated by current the temperature gradient in the dielectric and the electromagnetic effects arising from the circulating current so obtained—features not obtained where water-heating is adopted—have an important bearing on the behaviour of the dielectric. The temperature gradient certainly is an important factor, but I can scarcely believe that the electromagnetic forces between conductors carrying normal currents are of any importance at all compared with the mechanical force due to bending a cable. And what can be the advantage from the user's point of view in testing his cable with only a part of the dielectric heated to a known temperature, over testing with the temperature of the whole dielectric absolutely controlled? If there were any electrical weakness introduced by having a temperature which falls off in value from the conductor to the lead, there might be some reason for accepting the other disadvantages of this test, but I have never seen any evidence of such weakness. In case it may appear that my opinion is influenced from the manufacturer's standpoint, I may say that a cable always shows up better on dielectric-loss tests when tested by Mr. Ratcliff's method than when tested in water, for the simple reason that in the latter method all the dielectric is hot and not merely that part near the conductor.

Mr. Allen explained the method of analysis described by Steinmetz to demonstrate how a more exact expression than $I+At^{-n}$ could be obtained for the charging current of a cable dielectric. He produced some interesting curves and there is no doubt that Steinmetz's analysis of a charging-current curve into a series of exponential curves has all in its favour from a mathematical point of view. It does not at present, however, help us in co-ordinating the work of those investigators who have used the index n in the d.c. formula adopted in the paper for analysis of the a.c. conditions. Mr. Allen's remarks on the effect of light and heavy oils and finely divided air are valuable, but the examination of any such theory as he advances to explain the "V" curve would involve consideration of the various expansion coefficients of the different components of the cable, the oil, paper, air and enclosing envelope. This would be well worth following up. Mr. Allen also raised the question of the

effect of hot spots on the smoothness of the time-voltage curve. It is the author's experience that with 5-yard samples of a well-made cable with well-made pot ends the points generally do not depart far from a smooth curve.

Mr. Taylor's observations on the effect of intersheaths on puckering of papers in a single-core cable are of considerable interest, as, of course, anything which makes for compactness is an advantage from the electrical point of view.

In reply to Mr. Silver, I do not consider that tests of dielectric resistance can at present replace pressure tests. There are certain possible defects in high-voltage cables which, while causing failure in use, would not show up on a resistance test. For instance, imperfect impregnation may result in a high value for dielectric resistance, but the heating under alternating voltage would quickly produce failure. In reply to Mr. Silver's second query it is my belief that electrical breakdown is certainly a chemical action. Whether or not it always follows the conversion of the dielectric into a conductor by the passage of a current I should not like to say, but most decidedly it sometimes works that way, as can be easily seen by dissecting and examining a cable on which a prolonged test has been interrupted before actual failure.

Mr. Addenbrooke has put his finger on a very important point in showing how the subject of cable dielectrics is complicated by the fact that the conditions under which the dielectric works when made up into a cable are quite different from those holding when the dielectric is tested in a uniform field. I myself, as well as many other investigators, have appreciated this fact and am very chary of accepting results obtained on samples of material until they are confirmed on actual cables made with those materials. Mr. Addenbrooke's suggestion for explaining the " V " curve by an unstable equilibrium of moisture between the paper and oil is new to me, and is very interesting. I feel with Mr. Addenbrooke, however, that this is not the whole story, because some of my experiments show that the curve is not always entirely reversible. Repeating the loss tests at, say, 20° C. after a series of tests up to 60° C. does not necessarily give a repeat of the former 20° C. figure. The effect of pressure on resistance, Mr. Addenbrooke's second suggestion, would, I think, fit in better with these facts. The mechanical pressure generated during heating may cause some physical displacement which is not restored during cooling.

In reply to Mr. Owen, I am afraid that the scope of the paper, wide as it is, does not include glass dielectrics, but the subject of wave distortion in this material should, of course, be considered in any attempt at a complete theory, if we ever arrive at such a desirable end. In his second point, too, Mr. Owen has, I think, overlooked the title of the paper. Whilst there is nothing new in the time effect in the study of dielectrics in general, my contention that the phenomena has not been appreciated in connection with cables is fully supported, if further evidence is necessary, by the remarks of some of the leading cable users in this same direction. In replying to Mr. Ratcliff I have gone over very much the same ground as covered by Mr. Owen in the latter part of his remarks.

Mr. Beavis has contributed some interesting observations on the use of high-voltage d.c. testing for the detection of incipient faults, but in spite of the present popularity of " Delon " and " Kenotron " testing there is a good deal to be learned about the relative effects of high-voltage direct current and alternating current.

Mr. Schuil raised the same point and, in reply to him, I should say that a test of this kind should not be detrimental to a well-made cable. This speaker claims that the d.c. test penetrates deeper into the insulating layer than does alternating current. Well, I do not know about this, but I think that a certain form of deterioration leading to failure which accompanies a.c. testing is not found with direct current. In reply to Mr. Beavis's query about the tests recorded in Fig. 39, the original conditions did not return with time. The experiment on the improvement of power factor of a hot cable by plunging into cold water, as described by this same speaker, is interesting and is no doubt connected with the mechanical contraction of the lead sheath causing a high hydrostatic pressure within the dielectric, which is still expanded by the heat retained. In reply to Mr. Beavis's last point, the curves plotted from the temperature test suggest that the coefficient changes uniformly throughout the range.

Mr. Willmotte refers to the recent suggestion made by Mr. L. Hartshorn, that the seat of dielectric loss and absorption phenomena is in the region of contact between the electrode and the dielectric material. I have been very interested in following the steps in Mr. Hartshorn's theory, but have had difficulty in seeing why in a dielectric like that found in a paper cable, for instance, there is any more reason for the contact resistance at the electrode being more responsible than that between different layers in the body of the dielectric. This same investigator accepts the absence of residual charge in liquid dielectrics. My own results disprove this. He also claims that the power loss in a liquid dielectric is independent of frequency; Mr. Emanueli's contribution to the present discussion shows that this is incorrect. These points, and others not relevant at this juncture, make one think that there must be loss in the dielectric itself quite apart from the contact with the electrodes. Mr. Willmotte's suggested explanation of the " V " curve is subject to the same criticism, and his reference to Mr. Emanueli's curves is covered by my answer to this speaker.

No worker has given more serious thought on the theoretical side to the questions discussed in the paper than Prof. Thornton, and it is therefore very gratifying that he has contributed to this discussion so useful a summary of his views, many of which have already been published. Generally speaking, I agree with all that he says, but with one reservation. I cannot follow under his banner when he treats a cable dielectric as a perfectly homogeneous material. I think that all that he says would apply to a true dielectric, but when we are considering a laminated mass of paper, impregnated, not always perfectly, with oil and, from a chemical point of view, by no means dry, then I am

afraid a connected theory, based on elastic afterworking only, will leave a good deal unexplained.

Mr. Vernier's remarks on the progress which is being made in the Newcastle district in the use of cables for higher voltages are very welcome, as are also his observations on the present types of test employed in the acceptance of cables. I am sorry that he has any qualms about the methods adopted for dielectric-loss measurement. They are certainly complicated, but the order of accuracy usually obtained is easily sufficient to show the difference between a good cable and a bad one. I agree with Mr. Vernier that we badly need a more satisfactory test than any at present available. If the theory of failure which I have advanced in the paper is along the right lines, it is possible that a good ageing test could be obtained by employing a high frequency. If the deterioration is due to a local conduction current which flows to and from the local position through more perfect parts of the dielectric acting as condensers, then the rate of energy dissipation in the conducting portions will be proportional to the frequency, and possibly the effect of a year's life at 50 cycles may be imitated by a few hours on the same voltage at, say, 100 000 cycles per second. With reference to the work of Dr. Klein, quoted by Mr. Vernier, there does seem to be a certain amount of evidence for two types of deterioration, one which is temporary and one from the effects of which the cable never recovers, and the investigation suggested by this speaker would be a profitable line for study. As regards the tangential-stress theory of Höchstädter, far from decrying this I believe it to be right, but it is not the whole story. As advanced by the proposer, this theory does not explain, as mine does, why we can find tree-burning in the centre of the mass of dielectric on a single-core cable. I think that my theory on this point, taken in conjunction with Höchstädter's, brings us somewhere near the truth.

I have introduced into the text of the paper a few explanatory notes suggested by Mr. Maccall and would say that in adopting the inverse fourth root for the time-voltage curves, I have followed Peek. As the scale was convenient I have not troubled to search for an alternative. Probably there is a better one. As Prof. Thornton reminded us in the Newcastle discussion, the measurement of loss during a complete charge and discharge cycle has been done by Dr. Ashton. I cannot trace the application in the direction suggested, however. As to whether I consider the resistances to be real resistances, I see no reason why they should not be. Under the condition I have postulated in discussing breakdown (see Fig. 51), the resistance is a very definite entity. I have tested the relative effect of current- and water-heating on the "V" curve of loss and temperature, but never for the purpose suggested by Mr. Maccall. It might prove a profitable line of research. I have not considered that there is a very close connection between the methods of failure in a cable and an air-insulated wire, unless the correct insulation, impregnated paper, be partially replaced by air through imperfect manufacture, and then there may be a similarity.

Mr. Williams regrets that the cable manufacturers have not adopted sufficiently heroic measures in dealing with the difficulties of high-voltage cable dielectrics, and suggests a closer co-operation through the Cable Makers' Association and the Electrical Research Association to this end. I can assure Mr. Williams that although no claims are being made to the title "heroic," a very large amount of valuable research work is being done not only by the manufacturers individually, but also co-operatively through the C.M.A. and the E.R.A. Except in the case of out-of-date firms, there has been for some years considerable enthusiasm in investigating fully the problems of the dielectric, and up-to-date manufacturers need no urging either to investigate or to co-operate.

There have been several papers in the *Journal* of the American Institute giving the information asked for by Mr. Williams on the difference between the "V" curves obtained on the older and the modern types of compound. I cannot quote a set of figures which would give a simple answer to the question, but, generally speaking, the improvement consists in a flattening and a general lowering of the curve. I am sorry, too, that I cannot give any data relating to the "Höchstädter" type of cable which would be of use in a general discussion such as this. This form of construction is best discussed in connection with a particular proposition and compared with other standard types, as the question of cost enters very largely into the matter. The question of the connection between hydraulic pressures set up by loss and heating, and the nature of the "V" curve, is not an easy one on which to generalize. Variations due to the nature of the compound and the efficiency of the impregnating process make it impossible to draw any hard-and-fast conclusions at present. In my reply to Mr. Ratcliff I have referred to the method of heating a cable during the loss tests, but there is a further point calling for comment in Mr. Williams's remarks. My chief reason for supporting the water-tank method of heating, against the method of conductor heating, is that the whole of the cable is at one temperature. The lead is not hotter than the copper. On the other hand, under current heating it is absolutely impossible to state with certainty the temperature of any other part of the dielectric except that immediately in contact with the conductor, and then only an average value over the length of cable is possible. On the question of the reliability of loss tests, I would refer Mr. Williams to my reply on the same point raised by Mr. Vernier.

In reply to Mr. Elkington, some data on the distribution of temperature throughout the dielectric of a cable have been given recently by Mr. Beavis,* but I do not quite agree that the change of dielectric constant with temperature is of much consequence in explaining tree-burning. As is well known, the dielectric constant of a paper cable does not change to any marked extent over a temperature range of, say, 20° C. to 60° C. I agree with this speaker's last point that the position of tree-burning is probably settled as much by the nature of the gas in the space considered as by the temperature or stress, and that the kind of

* E. A. BEAVIS: "High-Voltage Cables," *Electrical Review*, 1925, vol. 97, p. 413.

impregnating fluid may have a marked influence in this respect.

Mr. Grant's observations on surges are of value in showing the type of protection that should be employed to ensure that under conditions of exceptional pressure-rise the energy is dissipated in the protective gear rather than in the cable dielectric. Possibly the antipathy shown by other speakers towards surge protection may be due to their having had experience of the unsatisfactory types referred to by Mr. Grant.

Mr. Nixon wants my opinion on graded dielectrics. I cannot speak for the future, but, so far, I have seen no really satisfactory evidence that grading a dielectric has ever increased its breakdown strength under service conditions, and I fail to see how grading can affect the problem of testing. I certainly agree that high-voltage tests may damage a cable dielectric, but I think that Mr. Nixon's definition of factor of safety is weak. Suppose, for instance, a piece of inferior cable to work at 33 kV stood 66 kV for one hour. Then Mr. Nixon would say that it had a factor of safety of 2. Now that same cable, if put on 33 kV, might fail in 100 hours. Could it then be claimed that such a cable had any factor of safety at all? As I have pointed out in replying to Mr. Ratcliff, a satisfactory definition of factor of safety is difficult, if not impossible.

Mr. Beaver implies a good deal of unexpressed criticism in the opening part of his remarks. I will accept the challenge on the relative importance of the physical, chemical and electrical properties of a cable, and will point out that, after all, it is the electrical properties which are of ultimate importance. A study of the chemical and physical properties is the best path along which to travel in improving the quality; but the effects of alteration in design, material and workmanship should all be traced right through to the electrical results, including, of course, those which allow for the effect of time. I think, too, that there can be little ground for any suggestion that I have gone too far on the mathematical side. Mr. Beaver criticizes at some length my suggestion to account for failure preceded by tree-burning, but his objections rather beg the question. In the first place, as stated clearly at the head of the list of phenomena on page 122, I am referring to the theory of breakdown explained on the same page, and not to the I^2R theory discussed earlier in the paper. On the second point, it is not really material to the operation of breakdown on the lines suggested, whether, once the lines of current flow are diverted from a radial to a tangential direction, they travel in the material or through conducting threads of ionized gas. The point which I have tried to make is that a certain current flows through the dielectric, shown in Fig. 51, between the conductor and the sheath and that this is at one part of the path purely a non-heating displacement current flowing radially, and at another part a heating current through having to flow circumferentially. This is most certainly not the pyro-electric theory of Wagner. In view of Mr. Beaver's remarks I think that I ought to amplify point (vi) on page 122. Accepting the long-employed logarithmic formula for maximum stress, the failure in a single-core cable should always be near the core. Add to this the fact that the losses cause the dielectric to be hottest near the conductor, then there should be no doubt that an interrupted prolonged pressure test should always show the deterioration to be at the parts subjected to maximum stress, i.e. near the conductor. What do we find in practice? The burning is anywhere and is by no means confined to the part of the dielectric around the conductor.

I am glad to have Mr. Beaver's support on the probable effect of an intersheath and the necessity for surge protection. We are also fortunate in having the results of this experiment, which are illustrated in Figs. H, J and K, now placed on record. He sums up this section by claiming that the evidence is more in accordance with the ionization theory than with mine. Personally, after examining the evidence in cold print, I find that there is not much to choose between the two, or, better, perhaps a combination of both theories may be the true explanation. Ionization of the air in the wormings only would certainly not account for what we find on dissecting a cable, tree-burning along the line of contact between cores on several papers down from the outside of the core. The suggestion which I have made would, however, do so.

Mr. Beaver's objection to migration of compound under stress, as postulated in the paper, is not easy to understand. It does seem reasonable, in view of experiments on electrodes and, what is more important, it has been actually observed in cables subjected to high-voltage tests.

Mr. Hawkins is rather afraid that his championing of the Höchstädter type of cable and discussion of the "S.L." type, on which I have published comments from time to time, may be considered to be irrelevant to the subject under discussion, but I think his observations are decidedly admissible. I can reply to the whole of his remarks very briefly by saying that I do consider that even for pressures as low as 33 kV, cables built on the "S.L." principle would have a greater reliability than the ordinary 3-core type.

Mr. Crellin has difficulty in seeing how a combination of resistances and condensers can represent the true physical action in an absorptive condenser, but I think he is overlooking the fact that I consider an infinite number of these units in combination, a mathematical abstraction certainly, but not an altogether impossible conception of the mass of a dielectric. The resistances with the high value are not those which carry the heavy current. This same speaker cannot accept the time function in breakdown; but here, I think, his difficulty is due to a loose interpretation of the word "instantaneous." I hope that one day somebody will investigate the time-voltage curve for very short time-intervals. I am certain that when this is done the present type of dielectric will still show the time effect. On the last point raised by Mr. Crellin, the suggestion I advanced to explain cable breakdown was never intended as a theory of the breakdown of pure and homogeneous dielectrics. That is a much more difficult field.

In reply to Mr. Philip's question on the allowable moisture in cable, I should say that no moisture is allowable, but as to how much gets in against the

regulations, I should not care to give a figure. It is certainly very much smaller than the figure which he quotes and is a most difficult quality to measure. On the use of the absorption index n, it is of no use applying the index obtained on long time-intervals for 50-cycle a.c. work. To obtain the calculation suggested, the index would need to be measured over time-intervals of the order of 1/100 second.

This answers a question put by Mr. Churcher, whose confirmation of the views advanced on change of power factor with frequency is very interesting. I think the reason that this speaker has not found the fall in power factor with rise of temperature, is because he has been working on a poorer class of dielectric, equivalent to the upper temperature range of impregnated paper where the "conduction" losses predominate. I agree with Mr. Churcher that the heating caused by dielectric loss may have a considerable effect on the power factor. This is shown very conclusively by recording the losses over a period of half an hour or so after switching on the voltage. They rise asymptotically to a maximum.

The points raised in the early part of Mr. Davey's remarks have been dealt with in replies to other speakers. His observations on the effect of frequency on power factor are a very useful contribution to the discussion and, in part at least, must be admitted. I think, however, that some of the specific objections raised are connected with the distribution of the vectors in Fig. 21. This is a real mathematical difficulty. In discussing the connection between the absorption index n and the a.c. power factor, it should be remembered that all the values which I have determined are for periods of time longer than 15 seconds. As previously explained in reply to another speaker, it would be necessary to obtain the values for very short time-intervals in order to use them for a.c. calculations. Mr. Davey claims that my explanation of the motion of the impregnating compound near a weak patch is opposed to a fundamental law of the dielectric circuit. I suggest that he should carry out the following experiment: Take two flat metal electrodes, a lower one 12 in. diameter and an upper one 3 in. diameter. Place a sheet of impregnated paper between them and apply a few thousand volts (a.c.). The impregnating compound will not move into the strong field between the electrodes, but will pile up all round the electrodes about an inch away, leaving the intermediate space dry.

I am glad to have Mr. Carr's confirmation of my own observations on incidence of tree-burning in the dielectric and on the difference in the nature of the discharge between that along a paper and through it. I would add, however, that papers which show the blackening described are still blackened after being thoroughly washed in naphtha, so that there is more than deterioration of compound. The analogy of a chain having a weak link, used by Mr. Carr, is a dangerous one when applied to a cable. One single broken link in a chain results in a broken chain and complete catastrophe. This is, however, not the case in a cable; a string of links joining the conductor to the lead must all fail before ultimate breakdown occurs, and this does not always follow immediately on the failure of one part.

REVIEWS OF PROGRESS.

The Council decided last Session to publish in the *Journal* periodical reviews of progress in electrical engineering, and for this purpose the subject has been divided into the following 13 sections :—

- *Electrical Plant and Machinery (including Marine Work).
- *Power Stations and their Equipment.
- Transmission and Distribution.
- Industrial and Domestic Applications (including Illumination).
- Electricity in Mining.
- Traction.
- Measuring Instruments (including Tariffs) and Sensitive Controlling Apparatus.
- *Telegraphy and Telephony.
- Radio-telegraphy and Radio-telephony.
- Electro-chemistry and Electro-metallurgy.
- *Electro-physics.
- *Research.
- *Standardization.

Whilst it is hoped eventually to publish each year reviews of all the sections, a beginning is made this year with the sections marked with an asterisk, and two appear below. A further selection will appear in 1927, and subsequent action will be based on the experience gained during the first two years.

These reviews have been prepared with a view to recording briefly recent advances, and they are intended, not so much for the information of experts in the particular subject under review, as for the information of those members of the Institution who wish to follow the trend of progress in branches of electrical engineering other than their own.

The Council will be glad if members will forward to the Secretary of the Institution any criticisms which they may wish to make on the present reviews, and also on the ground to be covered by those to be published in the future, more especially in regard to points of interest which come under their notice and on which they consider comment might usefully be made in the reviews.

ELECTRO-PHYSICS.†

By Prof. A. O. Rankine, D.Sc.

At the present time the appropriate, indeed the almost inevitable, starting-point for a report on progress in any branch of physics is the consideration of the constitution of atoms of matter. It is now generally accepted that atoms are electrical structures, and that their properties must be capable of being harmonized with electrical laws. This very fact makes it difficult to prescribe limits to the scope of a subject termed "Electro-physics." The position is being rapidly approached in which all physics must be regarded as electro-physics, and the interconnections between what have been historically distinct branches of the subject are already so numerous and important that they cannot be disregarded. In the present report an attempt will be made to confine attention to the phenomena associated with electricity in the sense generally understood in the past, digressions being followed only so far as the necessity for logical presentation demands. We begin, then, with a statement of the progress of atomic theory, and afterwards consider it in relation to some of the chief experimental facts of electricity and magnetism.

Structure of the atom.—The general outcome of recent research has been steadily to bring confirmation to the nuclear theory of the atom proposed some years ago by Rutherford, namely, that atoms consist of very small positively-charged central bodies surrounded by a number of electrons at relatively great distances. In a neutral atom the charge on this nucleus is equal to the sum of the charges of the electrons, each of which has an invariable charge of $-4 \cdot 77 \times 10^{-10}$ electrostatic C.G.S. units. The nucleus possesses practically the whole mass of the atom, the electrons contributing only a very small fraction.

The characteristic property of an atom is the electrical charge of its nucleus, or the number of electrons surrounding it in the neutral condition. This number is called the "atomic number" and determines the position of the element in question in the periodic classification previously arranged according to atomic weights. Thus the atomic number of hydrogen is *1*, of helium *2*, of lithium *3*, and so on up to the number *92* which belongs to uranium. In every case it is the factor which determines the chemical properties of the atom. Most of the atoms between *1* and *92* have been identified with known elements; only two or three gaps remain, one having been filled recently by the remarkable discovery of hafnium (atomic number *72*) referred to later. The possibility of the future discovery of atoms with higher atomic number than *92* is, of course, not excluded.

The outer part of the atomic edifice.—So far the theory of atomic structure finds general acceptance, but there persist two widely divergent views as to the condition of the electrons outside the nucleus. The application, initiated by Bohr, of the quantum theory to the nuclear atom demands that the electrons are describing orbits of specified characters round the nucleus, and that radiations visible or invisible occur only when electrons jump from one orbit to one possessing less energy. The development of this theory in the hands of Bohr and others has been so remarkably successful in accounting for the spectra emitted by excited atoms, besides other phenomena in the physical domain, that most physicists

† Reprints, in pamphlet form, price 2s. 6d. each, can be obtained from the Secretary of the Institution.

regard it as fundamentally true.* On the other hand, chemists have been attracted to the theory propounded by Lewis and Langmuir, which supposes the electrons in the atom to be stationary, or nearly so, because it has been serviceable in accounting for the chemical combinations into which atoms enter. A completely acceptable theory must account for all the facts, and for this we have still to look to the future.

The atomic nucleus.—Important progress has been made in the investigation of the structure of the atomic nucleus, mainly in the Cavendish Laboratory. As will be seen, the results lend further support to the view—now several years old—that the nuclei of atoms have common constituents—that they are, in fact, built up of electrons and their counterparts, the so-called "protons," closely packed together. The proton is identified with the nucleus of a hydrogen atom, and although its charge is equal and opposite to that of an electron, its mass is 1 800 times as great as the electron mass. According to this view, therefore, the atomic mass is determined almost entirely by the number of protons the nucleus contains, while the atomic number is equal to the *excess* of the number of protons over the number of electrons *in the nucleus*. The mechanism of the equilibrium of such systems of electrons and protons remains for the present unexplained.

Isotopes and Isobares.—The significance of this nuclear theory is of fundamental importance. It provides an explanation of the existence of so-called "isotopes," besides being in harmony with the facts of the disintegration and transformation of atoms, both natural and artificial. Isotopes are atoms of the same chemical properties, and therefore having the same atomic number, but with different masses or weights, and their discovery in the radio-active sequences of elements has been followed by proof of their existence in many non-radio-active elements also. The proton-electron theory of the atomic nucleus is in keeping with these results, for clearly an increase in the number of protons in the nucleus, accompanied by an equal increase in the number of electrons, does not change the atomic number. A further possibility suggested by the theory is the existence of atoms of the *same* mass, i.e. with equal numbers of protons in the nucleus, but with different atomic numbers, owing to the number of nuclear electrons not being the same. Such atoms would possess quite dissimilar chemical properties, and are already known in the radio-active series. They are called "isobares."

Much progress has been made during the past year or two in the investigation of isotopes and isobares, chiefly by the continued work of Aston on measurements of positive rays with the mass spectrograph. This method enables the masses of *individual* atoms to be measured (as distinct from the *average* mass obtainable by chemical means), and has proved indisputably that many elements are mixtures of isotopic atoms, and, moreover, that each individual atomic mass is a whole number of definite units, which theory identifies with protons. A recent list is given by Aston in the Royal Society 1925 Wembley publication "Phases of Modern Science," pp. 43 and 44, from which it appears that some elements, tin, for example, are mixtures of at least seven isotopes, and possibly more. The existence of isobares has also been definitely established, although the occurrence so far is relatively rare. A notable example is the case of argon and calcium, both of which consist of two isotopes. The principal constituent of each has a mass equal to 40 protons, while the atomic numbers, which determine the widely different properties, are 18 and 20 respectively.

Atomic disintegration and transformation.—Further evidence in favour of the proton-electron structure of the atomic nucleus is provided, as already mentioned, by both the natural and artificial transformation of atoms. The corpuscular radiation from the radio-active atoms during the process of spontaneous disintegration has long been known to originate in the nucleus. It consists of two distinct entities, the α particle and the β particle. Of these the β particle is a high-speed electron, and the α particle has been proved to be identical with the nucleus of the helium atom, possessing a positive charge equivalent to two electronic charges. The evidence of radio-activity thus proves that electrons are among the constituents of at least some atomic nuclei, and that the positive nuclear component is capable of splitting up into smaller parts. For definite proof that there are protons in atomic nuclei one must turn to the remarkable experiments of Rutherford and his collaborators on the controlled disintegration and transformation of atoms, recent accounts of which may be found in the *Proceedings of the Royal Institution*, 1923–25, vol. 24, p. 585, and in "Phases of Modern Science," pp. 30–36.

The experiments generally consist of observing the effects of bombarding materials with α particles from radio-active preparations—natural projectiles which in their combined speed and mass transcend in effectiveness anything obtainable by artificial means. These positively-charged projectiles are able to approach closely to the nuclei of the bombarded atoms in spite of the electric repulsion, and, in the case of atoms of small atomic number or small nuclear charge, to collide directly with the nucleus. Such collisions are, of course, very rare events, owing to the minuteness of both target and projectile, but when they do occur disruption may result, and a proton may be ejected from the nucleus with high speed. Rutherford has shown that all the elements between boron and potassium in the atomic classification, with the exceptions of carbon and oxygen, may be disintegrated by this means. Perhaps the most remarkable of all the results is the series of photographs Blackett (*Proceedings of the Royal Society*, A, 1925, vol. 107, p. 349) has obtained by an adaptation of the Wilson condensation ray-track apparatus, showing the tracks of particles in gaseous nitrogen. Over 400 000 such tracks were photographed, and of these eight displayed the track of a proton ejected from a nitrogen nucleus together with that of the recoiling nucleus itself. But no trace was found of the continued track of the original projectile—the α particle—and Blackett has concluded that it was captured in the collision. On the accepted nuclear theory

* Prof. Bohr, in an article just published (5th December) in the supplement to *Nature* (1925, vol. 116, p. 847), appears to anticipate that the developments of his theory will necessitate the abandonment of this view of atomic structure. He says: "In contrast to ordinary mechanics, the new quantum mechanics does not deal with a space-time description of the motion of atomic particles"; and again, "To the physicists it will at first seem deplorable that in atomic problems we have apparently met with such a limitation of our usual means of visualization." It is certainly disturbing, coming from such a source.

this would signify that the nitrogen atom has on the whole gained both in mass and in nuclear charge; for, while it has lost one proton and one positive charge, it has gained an α particle (which has the mass of 4 protons) and two positive charges. Its mass, originally 14 protons, has increased to 17 and its nuclear charge, originally 7, has increased to 8, which is the atomic number of oxygen. The nitrogen atom is thus regarded as having been transformed into an oxygen atom—an isotope of the usual variety.

Atomic energy and atomic transformation.—The possibility of changing one atom into another raises a question of great significance, namely, the equivalence of mass and energy as indicated by the theory of relativity. A mass m at rest may be regarded as energy of amount mc^2, c being the velocity of light. If in an atomic transformation the total mass becomes reduced, say to m', an amount of energy will be liberated, and presumably radiated, equal to $(m - m')c^2$. Aston's experiments show that the single proton which forms the whole nucleus of an atom of hydrogen has a mass 1·0077 times as great as that of protons in the nucleus of more complicated atoms. Thus if hydrogen became transformed into any other element, for example helium, the change would be accompanied by a reduction of mass and a liberation of energy which, although small in respect of each atom, would reach prodigious amounts for even 1 gramme of transformed substance. Such changes are believed by astronomers to be occurring in the stars and to be responsible for stellar radiation,* and although the question must still be treated with reserve, the possibility of the artificial liberation of atomic energy has to be contemplated for the future.

X-rays.—It is, however, in respect of the relations between radiation and the extra-nuclear electrons of atoms that progress has been most rapid in recent years. An atom radiates electromagnetic waves only when one of these electrons revolving round the nucleus suddenly jumps from one orbit to another. The mechanism of this transfer is not yet understood, but there appears to be no doubt that the frequency of the radiation is determined by the reduction of orbital energy associated with the transfer. This is, in fact, a statement of the quantum theory as applied to atoms; atomic radiation takes place, not continuously, but spasmodically and in definite amounts or quanta to which the frequency of the radiated energy is proportional. In the case of atoms of small atomic number, i.e. atoms with small nuclear charge and few orbital electrons, the energy changes in the possible orbital transfers are such that the radiation frequencies are in or near the visible region of the spectrum. So also are the radiations even for atoms of high atomic number if only electrons in outlying orbits are disturbed. Very great progress continues to be made in the examination and interpretation of ordinary spectra in relation to the theory here briefly indicated. It is now believed also that X-rays originate in the same way as ordinary visible spectral lines, except that the electrons which produce them are those occupying the inner orbits of atoms of sufficiently high atomic number. To measure the high frequencies and short wave-lengths of these rays, prisms and artificially-ruled diffraction gratings are too coarse, but the regular arrangement of atoms in crystals has fortunately provided natural diffraction gratings of sufficient fineness.

In order that an atom may radiate it is necessary that its electrons should be displaced from their normal orbits to more distant ones possessing greater energy, so that the energy may be re-emitted in the process of returning. The atom has, in fact, first to be excited. Excitation may be effected in a variety of ways, the chief of which is by means of bombardment by swiftly moving electrons such as, for example, the cathode stream in a vacuum tube. The extent of excitation depends on the speed and energy of the bombarding electron; it cannot produce an energy change in the bombarded atom greater than that which it itself possesses. With the high-speed electrons proceeding from the cathode in an X-ray tube subjected to high voltage the deep-seated orbital electrons in the atoms composing the anticathode are sufficiently disturbed, and, in returning to these inner orbits, they emit the characteristic X-rays of the element in question. These characteristic rays have frequencies depending, according to the Moseley law, on the atomic number, and they have been determined for most of the heavy atoms. A most remarkable achievement in this connection was the discovery of the new element hafnium by means of the characteristic X-rays which it produced when the preparation suspected of containing it was placed on the anticathode of a tube. The identification of this hitherto missing element of atomic number 72 was announced by Coster and Hevesy in 1923, and since then numerous other of its properties have been determined in Copenhagen. These are recorded in a monograph by Hevesy, entitled "Recherches sur les Propriétés du Hafnium." *

Ionization potentials.—The excitation of an atom may proceed to such an extent that one or more of its electrons are actually ejected completely from the atomic edifice; in such a case the atom is said to be ionized. If the agency of ionization is the bombardment by electrons, the electron energy must exceed a certain minimum, characteristic of the bombarded atom. The voltage through which the electron must fall in order to acquire this minimum speed is called the "ionization potential" of the atom thereby ionized. Much work has been done in measuring these potentials for different gases, the values being of great importance in connection with the theory of spectra.

Photo-electricity.—There is, besides, another agency for producing ionization, namely, radiation of suitable frequency. It is in this field that the quantum theory has derived some of its most convincing support. The photo-electric emission of electrons from atoms occurs only when the frequency of incident radiation reaches a minimum or "threshold" value. Thus if W is the

* In this connection reference must be made to the recent remarkable discovery by Millikan of high-frequency rays of cosmic origin described in *Nature*, 1925, vol. 116, p. 823. These rays, which are of far greater penetrating power than any hitherto known, are apparently reaching the earth's surface with equal intensity in all directions and at all times. The frequency of the hardest of them is probably 50 times that of the hardest γ rays from radio-active sources, and the wave-length correspondingly short, namely, 4×10^{-12} cm.

Millikan draws attention to the fact that the frequency of this part of the new radiation corresponds, according to the quantum theory, to the energy change in the hydrogen-helium transformation here referred to, and suggests this change as the possible origin of the rays in remote spiral nebulæ.

* Published by Det. Kgl. Danske Videnskabernes Selskab.

work necessary just to remove an electron from an atom (this depends, of course, on the nuclear charge and the particular orbit occupied by the electron) and the threshold radiation frequency is ν_0, the quantum relation $W = h\nu_0$ holds, h being Planck's universal constant. No electrons are emitted for frequencies less than ν_0, but when the incident frequency ν is in excess of ν_0, the balance of the energy $h\nu - W$ appears as kinetic energy of the ejected electron, so that

$$h\nu - W = \tfrac{1}{2}mv^2$$

m being the mass of the electron, and v the velocity after ejection.

This relation was first established for the atoms of the alkali metals, each of which has a loosely bound electron capable of ejection by the relatively low frequencies of visible radiation. Their photo-electric properties are now being extensively made use of in so-called photo-electric cells, which have numerous practical applications such as the telegraphic transmission of pictures. But all atoms have photo-electric properties. To eject deep-seated electrons, very high-frequency radiation is necessary, and important work has been done, chiefly by de Broglie, on the electron emission from atoms in consequence of irradiation by very high-frequency X-rays. The measurement, by deflection in a magnetic field, of the velocities of the various electrons extracted under these conditions from an atom has provided, in conjunction with the quantum theory, a most effective means of examining the so-called energy levels of the atomic electron orbits. In addition, a similar examination of the relations between the γ-rays and β particles emitted from the nuclei of radioactive atoms appears to point to the existence of minute electron orbits actually within the nucleus itself.

Conduction of electricity.—The way in which electricity is transported under the action of an applied voltage is a question of fundamental importance. From the point of view of atomic theory we can be said at present to be only at the beginning of its explanation. The mechanism of the process is quite clearly understood only in the special case in which free electrons in a complete vacuum themselves move and thereby constitute the current, as in the hard X-ray tube, or in the thermionic valve. Conduction in gases, liquids and solids must, of course, ultimately also be completely explainable in terms of the theory, but that has not yet been done.

Conduction in gases.—The mechanism of the motion of electricity in gases is believed to be that of ionization of the atoms or molecules by electronic bombardment, by suitable radiation or by such agencies as α particles. The applied voltage causes the ions to move in the appropriate directions, and the current consists of these streams of ions. With gases at low pressure, as in a discharge tube, cumulative ionization may occur, thus enhancing the current. In other words, an ion may be able to move freely under the action of the voltage gradient, and thus gather sufficient speed to ionize the atom with which it eventually collides. The process, of course, is complicated by the recombinations which are continually going on. In the discharge tube the electrons proceeding from the cathode must be able to traverse unimpeded a range corresponding to the ionization potential, and the positive ions then formed are driven towards the cathode, and through it if it is perforated, thus giving the positive rays which, by being subsequently deflected by known electric and magnetic fields, give the isotopic mass spectra of Aston. A valuable account of the general nature of conduction in gases at low pressure has recently been given by Whiddington (*Nature*, 1925, vol. 116, p. 506).

Conduction in electrolytes.—The laws of conduction in fused salts and in solutions of salts have long been known, and they are in close accord with the view that the carriers are ions, i.e. atoms or groups of atoms which have gained or lost one or more electrons. There is evidence from the X-ray analysis of crystals of the salts that these transfers of electrons have already taken place in the solid, fusion or solution merely separating the positive and negative parts. Quantatively, atomic theory is in satisfactory agreement with the experimental laws of electrolysis, but the mechanism of this type of ionization remains obscure.

Conduction in metals.—Although we now know with precision the number of atoms in a specified piece of any metal and the number of extra-nuclear electrons in each atom—and therefore the total number of such electrons—the majority of the phenomena of metallic conduction still await a quantitative explanation. It appears to be certain, since the metallic atoms themselves are not transported, that the carriers are the extra-nuclear electrons, which have, therefore, an average velocity in the direction opposite to the nominal current direction. This *average* velocity can obviously be easily calculated, but gives no clue as to the fraction of the total number of electrons actually taking part in the transfer at any given moment, or as to the mechanism of their release from or re-combination with the stationary atoms. Reference may be made in this connection to the illuminating account of the motion of electricity in metals, given by H. A. Lorentz in the recent Lecture (May, 1925) before the Institute of Metals, in which, among other things, he draws attention to the experiments of Tolman and Stewart on the currents produced by the acceleration of a conductor. The magnitude and direction of these currents are such as to prove that in metals electric currents do consist of the motion of negative electrons.

Magnetism.—The theory of the atom described earlier would appear to have the elements necessary for the explanation of magnetism. A circulating electron is a current producing a magnetic field in the direction of the axis. Further, the application of a magnetic field to an atom might be able to impart to electrons additional circulation which would give rise to an opposing magnetic field. The latter effect would correspond to dia-magnetism; the former, combined with inter-atomic collisions, to para-magnetism. But the remarkable experimental work of Stern and Gerlach on the behaviour in magnetic fields of isolated atoms of various metals renders it necessary to revise the earlier views of the origin of magnetism. Briefly, these experiments, commenced in 1922 and still in progress,* consist of observing the deflections of vaporized atoms of the

* See W. Gerlach, *Annalen der Physik*, 1925, vol. 76, p. 163.

metal shot out from a furnace into a vacuum, when a non-uniform magnetic field is applied perpendicular to the atomic tracks. Some atoms—lead, tin and, oddly enough, iron—are unaffected by the field, and must be presumed in this isolated condition to have no magnetic moment. Others—copper, silver and gold—are deflected, but in such a way as to indicate that the atoms can occupy only two definite positions in the applied field. For the bearing of this on atomic theory in relation to so-called space quantization, reference may be made to the original papers and to a recent Royal Institution lecture by C. G. Darwin.*

One other very surprising experimental result must be mentioned. Glaser † has measured for the three gases H_2, N_2 and CO_2 the diamagnetic susceptibility at pressures ranging from 0–900 mm of mercury. The curves in each case indicate a notable change of susceptibility with reduction of pressure. At low pressures the susceptibility is proportional to the pressure; above this range the proportionality ceases, and this is followed at higher pressures by a new proportionality, with, however, a constant only one-third of the original value. So far no adequate explanation of the phenomenon has been offered.

Conclusion.—A report like the present one, with prescribed limitations as to length, obviously cannot be exhaustive. What has been done is to select for description certain outstanding recent advances in the subject. The omission of reference to many phenomena such as thermionics, thermo-electricity, piezo- and pyro-electricity, to mention some only, is due to the reporter being unaware of specially notable recent progress in these branches of electro-physics.

TELEGRAPHY AND TELEPHONY.‡

By W. CRUICKSHANK, Member.

INTRODUCTION.

In this, the first, review of the progress of telegraphy and telephony published in the *Journal* it may not be amiss to furnish a record to date of the magnitude of the undertakings under those headings controlled by the Postmaster-General in this country (which does not include the Irish Free State) so as to provide a basis for comparison in succeeding reports. The figures quoted, it should be understood, apply to the State industry only, and do not cover the railway systems or the innumerable private-wire installations erected and maintained by large industrial concerns.

Total single-wire mileage (working and spare) as at 31st March, 1925	5 222 424
Telegraph mileage (working)	273 010
Telephone mileage (working)	4 387 324
Telephone mileage, trunk lines (working)	669 753
Telephone mileage, local exchange lines (working)	3 717 571

The lines may be further subdivided into three broad classes—aerial, underground and submarine—the figures for which are as follows:—

Aerial wire mileage	1 106 375
Underground mileage	4 095 591
Submarine mileage	20 458
Total	5 222 424

The P.O. Engineering Department has developed methods of ascertaining construction and maintenance costs, extending over all districts and covering all classes of plant, and expresses the results in multiples of the man-hour unit.

The financial results of the working of the plant can be obtained from the Commercial Accounts published annually.

TELEGRAPHY.

Developments in this country.—A scheme of reconstruction is taking place in the Central Telegraph Office—which incidentally has squeezed out the Engineer-in-Chief and his staff from the G.P.O. West—and old telegraph men will have difficulty in finding their way through the galleries. The intercommunication switchboard, which provided direct switching between out-offices, is being replaced by lamp-signalling concentration switchboards, and by direct communication in the case of offices which have sufficient traffic to warrant junction lines. Additional lamp-signalling concentrators have been installed at Manchester and Edinburgh and a trial has been made of automatic concentration working, in which a calling line searches for a disengaged working set.

The method of superposing telegraphs on telephone lines, known as compositing, has been working satisfactorily on the circuits London to Penzance, and London to Chester, while the same system has been applied successfully to the telephone circuits working in the London–Brighton cable. The arrangement is a development of the original Van Rysselberghe method of introducing inductance in the direct telegraph lead, with a capacity shunt to earth, with the object of rounding-off the square fronts of the battery-derived telegraph signals and so preventing "morse thump" and disturbance on the telephone lines. The introduction of properly designed filters has resulted in the production of circuits which can carry both telegraph and telephone communications without serious interference with each other. The system is being used extensively in the United States.

An interesting example of the better-known method of superposing circuit on circuit has been introduced on the London–Penzance cable, where seven duplex high-speed telegraph loop-circuits are obtained on eight wires. Four loop-circuits are worked on the four physical pairs; one phantom circuit is superposed on pairs 1 and 2, another on pairs 3 and 4, while a third, which is known as the double plus, is superposed on the two phantoms.

When the telegraph circuits were first brought underground to avoid interruption from storms, working speeds were reduced owing to the greater capacity and resistance of the cable. Single-wire and earth-return circuits produced inductive disturbance, even when each

* *Proceedings of the Royal Institution*, 1925, vol. 24, p. 626.
† *Annalen der Physik*, 1924, vol. 75, p. 459.
‡ Reprints, in pamphlet form, price 2s. 6d. each, can be obtained from the Secretary of the Institution.

circuit was electrostatically screened from its neighbours by a copper tape, earth connected. Loop working was then resorted to, but as cable-balancing had not reached its present efficiency it was found necessary to use separate batteries not earthed in the centre, as in the case of the P.O. standard voltages for double-current working. Speed was increased by the use of a vibrating relay (based on the Gulstad principle) on the line, the auxiliary windings of which caused the armature to vibrate at approximately the speed of the incoming signals. Exhaustive trials are now being made with the standard batteries using a modified form of relay which, in addition to its auxiliary windings, is fitted with a double set of differential line windings. The relay is connected in the circuit, which is made up of the two wires of a cable pair, so that in a duplex circuit the compensation or artificial-line portion is connected between the two windings which are not joined to the line. The A and B wires, being joined to two equal windings, will—when subjected to external inductive interference—affect the relay equally and thus cancel out the trouble. To secure accurate balancing, double differential galvanometers are used in conjunction with the relays.

A similar circuit has been developed in the United States, where it is known as the polar duplex. A striking feature in the American circuit is the type of relay used. Permalloy is employed in the yoke, pole-pieces and armature. The last-mentioned is securely clamped at one end and passes through the hollow centre of the coil windings. The nickel-iron alloy is magnetized by a permanent magnet in such a manner that the ends of the armature are at equal magnetic potentials. The operating ampere-turns upset this balance and cause the free end to move in the required direction, its momentum increasing as it travels towards the local contact. To prevent rebound and chatter, the free end of the armature is fitted with flexible contacts which ensure a certain amount of rubbing contact without breaking. Two types of the relay have been devised, one fitted with auxiliary vibrating windings and one with double differential coils only. Extreme sensitiveness is claimed for the type, which enables the circuits to be worked with small voltages and correspondingly weak currents with minimum inductive effects on adjacent pairs. The circuits are worked on loops, and where telephone repeaters are fitted on all pairs by-pass channels are provided for the telegraph signals.

Progress of machine telegraphy.—Continued progress has been made in the direction of the supersession of morse-operated circuits by machine telegraphs. During the past two years the following Baudot circuits have been introduced :—

One quadruplex simplex, TSF—Boulogne and Lille.
One duplex 3-station, Leeds–Edinburgh–Belfast.
Eight duplex 2-station circuits converted to 3-station duplex.

In connection with the 3-station circuits, a new distributor table has been designed for re-transmitters and is being introduced at all intermediate stations on 3-station duplex circuits.

During the same period 22 duplex Morkrum teletype tape printers and 12 simplex sets have been installed. Eight of the latter have been fitted on private wires.

A second equipment of the Kleinschmidt column printer has been installed on the TS—Savings Bank lines.

Voice-frequency telegraphs.—Carrier-wave telephony —or wired wireless, as it has been called—has been operating successfully in this country for some time on selected trunk lines, but up to the present no working trial of the telegraph system based on the use of alternating currents of voice frequencies—say 200 to 2 000 periods—has taken place on actual lines, although successful trials have been made on artificial lines and spare pairs in the cables. The continual conversion from open line to underground working for other reasons is, however, turning the attention of the authorities towards the more economical utilization of underground networks, and it is probable that voice-frequency telegraphs will play a large part in the near future. The characteristics of valves as oscillators, amplifiers and rectifiers, and the application of filters for selective purposes have been fully investigated by the Department.

Two practical working systems have been devised, one in the States and the other in Germany. Both are worked on a multiplex simplex basis, two pairs of wires being utilized for working in two directions, one pair for sending and the other for receiving. Existing forms of telegraph apparatus can be utilized, and as far as the telegraphists are concerned they may each be working on direct physical lines. The sending and receiving apparatus of each arm can be assembled adjacent on the table, so that repetitions can be asked for exactly as on a duplex set, but no compensation circuit will be required.

In the American system, 10 frequencies, each a multiple of 85, beginning with 425 (approximately 2 670 radians per second) and going up by steps of 170, are utilized, the frequencies being produced by 10 small inductor alternators mounted on a common shaft and with a common field. Each of the 10 frequencies is controlled by a key or other sender and furnishes one arm of the multiplex. The frequency is first carried through a band filter, which eliminates or suppresses any harmonics that may exist, and is then passed on to common leads where it mingles, as it were, with the other 9 frequencies, each of which had been filtered in the same way. The common leads are terminated on the input winding of a valve-amplifier transformer, the output of which is joined to the sending line. At the receiving end the line terminates on an amplifier, the output of which is connected to common leads. From these common leads 10 receiving band filters select their own particular frequencies. Each frequency is then amplified, rectified, and operates its receiving relay. There are many special features employed which require too much room to describe.

The system devised by Messrs. Siemens and Halske is based on the same general principles. The main differences lie in the method of producing the oscillations and in the fact that the individual sending arm outputs are not filtered before combination. Oscillating valves

are used which are of the 3-electrode type; the combiner and amplifying valve has two grids, one of which is charged from an 80-volt tap off the 220-volt anode voltage, and the other primed negatively to approximately 6 volts. The common amplifying valve and the rectifying valves in each arm at the receiving end are also of the 4-electrode type.

The system has been tried experimentally on an artificial line and on a length of loaded underground cable at the G.P.O., and on each of the six arms with which the sets were equipped Wheatstone apparatus attained satisfactory working speeds of 100 words per minute. The frequencies used are 2 500, 4 000, 5 500, 7 000, 8 500 and 10 000 radians per second. These values can be regulated within certain limits by an adjustable iron plunger, which can be made to penetrate more or less deeply into the hollow core of each oscillating transformer.

The great advantage of the voice-frequency telegraph is that it can be used on underground telephone networks. The voltage impressed on the line is of the same order as that of telephone speech currents; hence inductive disturbances on adjacent circuits are minimized. Further, standard 4-wire repeaters can be employed on the circuits; uniformity of construction of cables can be secured and any pair can be taken indiscriminately for either telegraph or telephone purposes, due regard being paid of course to efficient balancing of the pairs in the cable.

Speeding up the telegraphs.—It is not surprising that proposals have been made to eliminate the comparatively highly-paid telegraphist by the process of short-circuiting him, the function of the public office being then merely to switch lines together. Mr. Donald Murray's paper on "Speeding up the Telegraphs" read before the Institution on the 18th December, 1924, advocated the introduction of teletype exchanges, which would afford the same facilities to start-stop telegraph-printer subscribers as telephone subscribers now enjoy. The paper opened up a fascinating vista, and the scheme cannot be thrown aside without the fullest consideration being given to its proposals. It may be that demands will come along in sufficient numbers to warrant mass-production, and the "Ford car of telegraphy" may then take its position as an essential part of the furnishing of every business-man's office.

Submarine telegraphs.—In this particular branch of telegraphy the past two years have presented a more drastic development perhaps than in any other. Karl Willy Wagner, in the October 1924 issue of *Elektrische Nachrichtentechnik*, describes the advent of wireless telegraphy as the Siegfried who wakened the dragon Fafnir guarding the Rhinegold of submarine telegraphy. Fafnir's dictum—"I lie and I possess; let me sleep"—is not strictly true when applied to the cable administrations, but the competition of wireless has certainly roused them to a keener sense of the need for faster methods of communication over the deep-sea routes. The introduction of Heurtley, Oerling, Sullivan and valve amplifiers, combined with the use of correcting networks to improve the incoming wave-front and to reduce distortion, increased the speed of working appreciably, but the recent development of continuous loading has so increased the capabilities of the cable itself that the line speed has now outstripped the receiving powers of the terminal apparatus.

Towards the end of 1923 the Western Union cable-ship "Lord Kelvin" sailed from Greenwich with a 120-mile length of permalloy-loaded cable, which she laid in 2 500 fathoms in a loop from Devonshire Bay, Bermuda. Both ends were landed, and a long series of experiments began. The trials were successful and, as a result, an order was placed with the Telegraph Construction and Maintenance Co. for a cable of similar construction, 2 400 miles long, to be laid between New York and the Azores. This cable was laid last year and the speed attained has exceeded even the most optimistic hopes. The permalloy tape with which the stranded copper conductor is wound is made of an alloy of 78·5 per cent nickel and 21·5 per cent iron. The tape is 6 mils thick and ⅛ inch wide, and is wrapped round the copper in a close helix, giving a uniform inductance of 54 millihenrys per nautical mile. The initial permeability of the tape is such that, if it were replaced by a continuous sleeve of the same thickness, μ would have a value of 2 300. A speed of 1 920 letters per minute was attained between Fayal and New York, after specially designed high-speed recorders had been devised to receive the signals legibly.

Before these results were made possible, a vast amount of patient research work had to be done. The difficulty of annealing the iron without injury to the copper had to be surmounted, after the best combination of nickel–iron had been determined to secure a minimum loss from hysteresis and eddy currents. Even after the cable had been laid, many problems arose. The question of the most efficient sea-earth, its length and relation to the depth of the cable at both ends to avoid extraneous interference and, above all, the best method of operating the cable with its high-speed possibilities, had to be considered. Most cables are worked duplex, but in this case the make-up, combined with the comparatively low propagation speed—which is not the same thing as the signalling speed—makes the balancing problem a most difficult one. Mr. Oliver E. Buckley, in the August issue of the *Journal* of the American Institute, discusses this point and says that to realize the full commercial advantages from the cable it should be worked on a multi-channel basis, say with a Baudot code, on a simplex up-and-down basis. There are reports that the cable will be ultimately operated sextuple multiplex, with re-transmitters or repeaters at the Azores, two arms New York–England, two New York–Germany, one New York–Italy, and one New York–Spain. Be these as they may, the fact remains that the permalloy-loaded cable has scored a distinct success and, it is understood, both the Pacific Cable Board and the Eastern Extension Co. have contracts for cables of similar construction in hand for operating on their America–Australian routes.

Although the Western Electric Co.'s engineers have been successful with permalloy, researches are being continued with other alloys, and it is understood that very good results are being obtained in this country with an alloy in which some 4 per cent copper is used, in addition to nickel and iron.

TELEPHONY.

In spite of the state of depression affecting certain sections of industry, the number of telephone stations in this country is ever increasing. If inter-communicating private sets were included, the number of telephones operating would be near the 2 millions mark; the number of stations, including exchange, private wire, call office and service lines, on the Post Office system amounted to 1 317 522 at the end of August, of which 462 007 were in the London telephone area and 855 515 in the provinces.

Colonel Purves, in his paper on "The Post Office and Automatic Telephones," read before the Institution on the 5th March last,* gave a complete statement of the automatic position in Great Britain. In Appendix 2 of the paper, a list of towns scheduled for automatic equipment is given; since the paper was read a start has been made with the manufacture or installation of such large equipments as those for Bedford, Burnley, Chesterfield, Coventry, Edinburgh (some 15 000 lines in four exchanges), Exeter, Kirkcaldy (completed), Sheffield Central (6 300 lines) and Southport. The whole of the Leeds area is now automatic, since the opening of Roundhay, Chapeltown and Headingley exchanges; Torquay and Paignton have also changed over to the new system, with through-dialling between the two towns. A number of orders are also in hand for extensions to existing automatic exchanges. The popularity of the private automatic branch exchange is evidenced by the fact that well over 70 separate installations of this type have been fitted or are on order in the last 12 months for large industrial and commercial firms. Many new manual exchanges and extensions to existing manual exchanges are in progress where economic necessities demand the continuance of hand operating. An elaborate scheme of direct dialling between automatic and automatic exchanges and between automatic and manual exchanges in non-director areas has been devised and is being introduced as opportunity and occasion require.

To provide for cable distribution from Wood-street, in the heart of the London area, where at least three 10 000-line exchanges are to be installed, a tunnel has been run under Wood-street from Gresham-street to London-wall and along London-wall to Moorgate-street, a distance of 660 yards. The depth of the tunnel is approximately 40 ft. and the diameter 6 ft. clear. Owing to the congested condition of the street, both above and below ground, and its situation in the danger area, there was considerable objection to the usual method of opening-up from above; in fact, there was no room in the subsoil for the large number of ducts required. At the exchange end the tunnel, which is lined with cast-iron segments similar to those used in tube-railway construction, is approached by an incline 8 ft. in diameter, making 35° with the horizontal, and three shafts approximately 4 ft. 5 in. in diameter are sunk at intervals along its length. The tube will be completed with a concrete floor, and bearers capable of taking 80 3-in. cables are fitted along both sides.

Position of automatic systems in the U.S.A.—The following details of the position of automatic development in the States (supplied by Mr. G. H. Nash of the Standard Telephones and Cables, Ltd.) may be of interest. It would appear that the policy is to install the panel system in the large areas, and step-by-step systems in the smaller. The figures dealing with the panel cover the period January, 1919, to September, 1925; step-by-step from January, 1903, to September, 1925.

(1) *Panel system.*

(*a*) *Exchanges installed.*

Total number of towns in U.S.A., excluding New York, in which panel exchanges are installed	20
Total number of exchanges installed in these towns	41
Comprising ..	220 000 lines
Number of panel exchanges in New York	27
Comprising ..	202 000 lines

(*b*) *Exchanges in Immediate Preparation.*

Number of new exchanges scheduled ..	27
Of these 27 exchanges, number to be installed in New York	5

(2) *Step-by-step system.*

(*a*) *Exchanges installed.*

Total number of towns in U.S.A. in which exchanges of over 100 lines are installed	146
Approximate number of exchanges installed	235
Of these, approximate number in Los Angeles	20
Total number of towns in which exchanges of less than 100 lines were installed up to August 1922	31

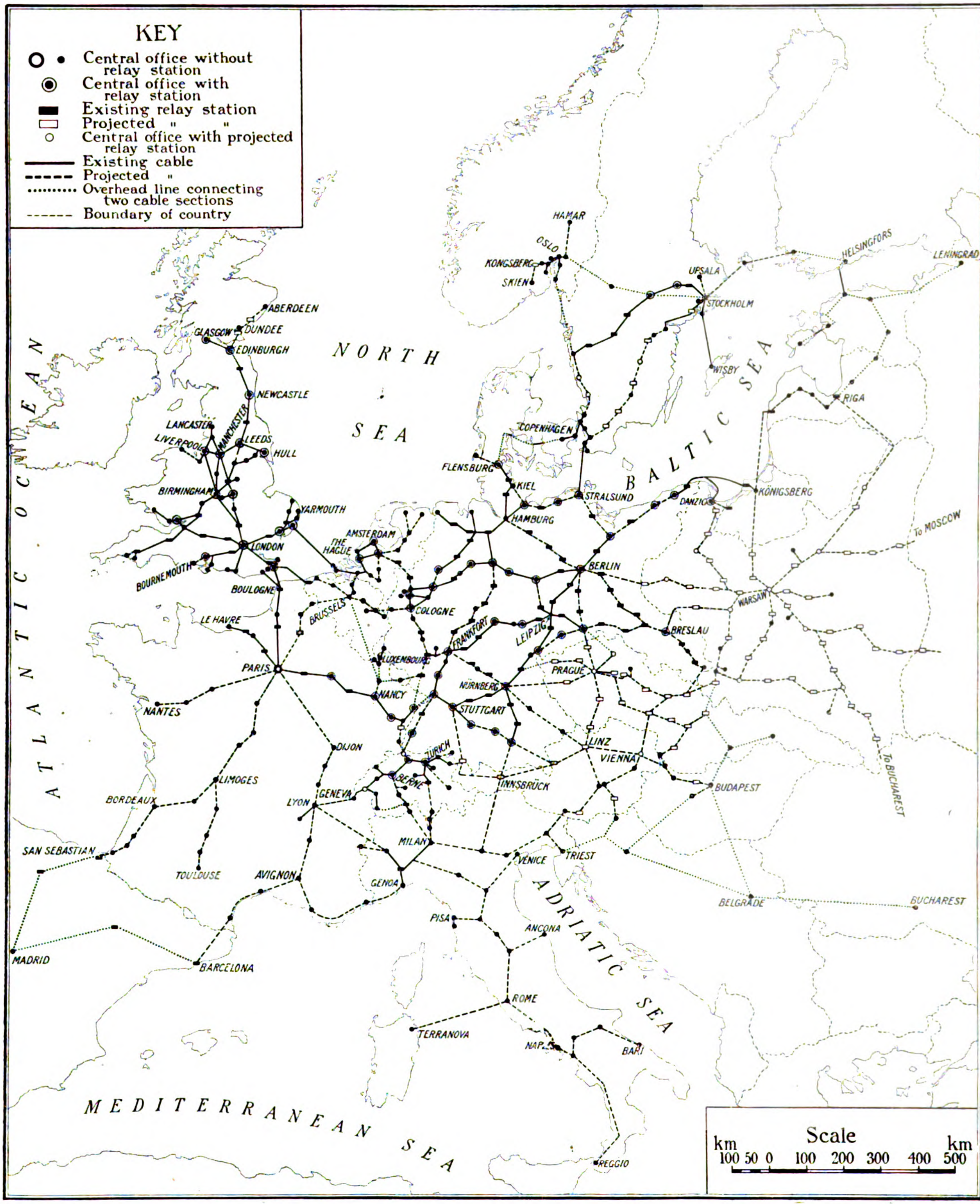
(*b*) *Exchanges in immediate preparation.*

Number of new exchanges scheduled ..	51
Of these 51 exchanges, number to be installed in Los Angeles	4

The position in Europe.—In Mr. F. Gill's presidential address to the Institution in 1922, he urged the development of intercommunication and the organized erection of trans-European trunk lines. On the 12th March, 1923, the first meeting of the Preliminary Technical Committee of representatives from Belgium, Spain, France, Italy, Switzerland and Great Britain, was held in Paris for the purpose of considering from the technical point of view the study of the problem of long-distance telephones in Europe. In May of the following year the International Advisory Committee, composed of representatives from Germany, Austria, Denmark, Finland, Hungary, Lettland, Luxemburg, Norway, Holland, Poland, Serbia, Croatia and Slavonia, Sweden and Czecho-Slovakia, as well as those from the original consulting countries, considered and adopted bases relating to the following questions:—

Transmission questions, traffic questions, maintenance and survey of lines. Since then, standard specifications for the supply of international cables and apparatus have been drafted, methods of measurements have been agreed upon, and dispositions relating to the

* *Journal I.E.E.*, 1925, vol. 63, p. 617.



Map showing International Telephone System of Europe.

measures required for the protection of telephonic lines from interference by power systems have been set out. Some controversy arose as to the best method of stating the efficiency of lines and apparatus, and the transmission unit has not been agreed upon at the time of writing.

The various units used or proposed from time to time may be stated as follows :—

(*a*) A mile of standard cable. The standard cable in this country is an air-space paper-core cable with the following constants per loop mile: resistance 88 ohms, inductance 0·001 henry, leakance 10^{-6} mho, capacity 0·054 microfarad.

(*b*) The 800-cycle mile. This unit has an attenuation equal to that of a standard cable mile at a frequency of 800 per second.

(*c*) The attenuation constant β. The natural unit based on the physical characteristics of a long uniform line and used in all theoretical calculation work on line-transmission problems.

(*d*) The decie. A tenth of β and suggested as a more convenient dimension.

(*e*) The transmission unit of "T.U." adopted in America. The transmission loss is 1 unit when the ratio of the power being transmitted between two points in the circuit is equal to $10^{0 \cdot 1}$. The main opposition to the use of this unit arises from the necessity of using a factor to convert logarithms from the natural base *e* to the base 10. America has been asked to send representatives to the next conference, and they will submit arguments in favour of the adoption of the "T.U." as the international standard.*

The accompanying map, showing the present position of the layout of the main European trunk routes, will give an indication of the progress made towards the linking-up of international communications and the extent of the programme. Conversations have been carried out successfully between London–Rome and London–Stockholm, but reliable service of commercial quality over these distances has not yet been attained. The London-Stockholm line, it will be observed, includes two lengths of submarine cable.

The French Administration has adopted a standard subscriber's telephone set with a view to securing a higher grade of transmission from the sending end than has hitherto been possible.

Underground cable problems.—The provision of underground networks on main trunk routes, fitted at regular intervals throughout their length with repeaters, has produced many new problems which were undreamt of when substantial copper wires widely spaced on the poles were the only means of communication. These problems have received careful study in the P.O. Research Section, and a résumé of the conclusions may be interesting.

First of all, the greatest care must be taken in the factory and on the road to secure uniformity of mutual capacity along a cable, so that a simple yet accurate balance (to simulate the line over the audio-frequency range) may be obtained at the repeater.

Secondly, lighter loading (i.e. a smaller amount of added inductance per mile) is desirable on longer circuits, for the following reasons :—

(*a*) To reduce the propagation time and so prevent echo effects. (Incidentally a very successful form of echo suppressor has been devised for 4-wire circuits. On long uniform overhead lines an echo is produced only by terminal reflection, and the transmission time is so short that the echo is merged in the main speech wave. Out-of-balance conditions at repeaters, inequalities in circuit characteristics and similar reflecting sources produce "echoes," and their interference on a loaded line degrades the articulation, a result liable to be amplified in the repeater. In the echo suppressor mentioned, an amplifier-rectifier valve in the "go" line is made to impress a quenching voltage on the grid of the amplifying valve in the "return" line, so as to reduce its efficiency and thereby cut off the echo.)

(*b*) To reduce transient disturbances and limit the distortion of the higher frequencies. Distortion is caused by the wave-length and amplitude of higher frequencies varying at a different rate from those of lower frequencies. The extent to which distortion can be reduced is limited by a number of conflicting considerations.

(*c*) To raise the cut-off frequency. The latter is that point on the curve of the attenuation constant plotted against frequency where the attenuation rises very rapidly and corresponds to a value of $\omega = 2/\sqrt{(LC)}$, where ω is the frequency in radians per second, L is the inductance per coil, and C the capacity per loading-coil section. Since loading has the effect of reducing the cut-off point, it is desirable, in order to preserve the essential qualities of speech, on longer lines involving many amplifications to cut off at higher frequencies than on shorter lines, even at the expense of an increased attenuation constant per mile.

The twisting of wires in pairs and the twisting of pairs should be carefully carried out to reduce unbalance and cross-talk, which would be amplified at repeater stations.

The relative advantages of twin, multiple-twin and star-quad formation may be summed up, for the types of cables used up to the present, as follows: More pairs for a given size of sheath and loop capacity can be placed in a multiple-twin than in a twin cable, and more still in a star-quad, the relative number of pairs being approximately, taking 100 in a twin as a basis, 113 in a multiple-twin and 135 in a star-quad. The disadvantage of the two latter types lies in the fact that the two pairs in a core run adjacent all the way and it is necessary to keep down unbalance between them. The capacity of a phantom circuit in a multiple-twin is 1·62 times that of the loop capacity, but as its resistance is only half that of the loop the phantom is more efficient than the side or physical circuit. In the case of a star-quad core the capacity of the phantom is 2·65 times that of the loop, and consequently the phantom is less efficient than the loop. The star-quad, which is used extensively in Germany, is made up of cores of 4 wires twisted uniformly together, a method formerly practised in this country, and will probably be used again, on account of its economy in space, in cases where phantom circuits are not likely to be required.

* At the December conference in Paris the U.S.A. representatives were present, but after full discussion the "T.U." was turned down by 5 countries to 3. Great Britain voted for "T.U."

Submarine cables.—The last two years have witnessed a considerable advance in the methods of manufacture of submarine telephone cable in this country. In August 1924 the first British-made lead-sheathed paper-insulated cross-sea cable was laid between Aldeburgh (Suffolk) and Domburg (Holland), and since then it has given excellent and continuous service, except for a breakdown last November, due, it is thought, to the fouling of a ship's anchor. The cable contains four quads—8 telephone loops—each conductor of which is made up of a centre copper wire, 76 mils diameter, surrounded by three copper strips 10 mils thick, and over these are wound two layers of 8 mils iron wire. A double lead sheath is fitted over the insulation to an external diameter of 1·52 in., and the cable is armoured with 24 No. 4 S.W.G., galvanized-iron wires. The overall diameter of the cable is 2·42 in.; its weight per nautical mile is 24·5 tons, and the total length is a little over 82 nautical miles. With a testing current of 1 mA, at a frequency of 5 000 radians per second, the attenuation constant per nautical mile came out at from 0·02001 to 0·02008 for the physical circuits and from 0·02365 to 0·02375 for the phantoms. The corresponding characteristic impedances varied from 410 $/\overline{6^\circ\ 22\frac{1}{4}'}$ to 418 $/\overline{6^\circ\ 15\frac{1}{2}'}$ vector ohms in the case of the loops and from 169·3 $/\overline{5^\circ\ 17\frac{1}{4}'}$ to 170·4 $/\overline{6^\circ\ 23'}$ for the phantoms. Cross-talk values ranged from 100- to 160-millionths of the impressed current from side-circuit to side-circuit, and from 800- to 2 000-millionths from side to phantom. The a.c. capacity was 0·097 μF and the insulation resistance 9 460–11 510 megohms per nautical mile.

Although this was the first type of paper-core, continuously-loaded lead cable laid in the North Sea, it is but fair to mention that the German Administration had laid similarly constructed cables in the Baltic about two years earlier, two to Sweden, two from Pomerania to East Prussia and one from Pomerania to Dantzig. The last-mentioned cable included four telegraph loops in addition to 8 telephone loops, and is about the same length as the Anglo-Dutch cable.

A 4-wire core, continuously-loaded, balata-insulated cable has just been completed for the New Zealand Government which will be laid between the North and South Islands to connect up the trunk system already existing there. The overall length is a little over 50 nautical miles. Under the same testing conditions as given above, the two pairs and phantom characteristics were as follows :—

	Attenuation constant per naut loop	Characteristic impedance in vector ohms
Pair 1	0·02726	252·7 $/\overline{6^\circ\ 1'}$
Pair 2	0·02733	251·2 $/\overline{6^\circ\ 13'}$
Phantom ..	0·02695	121·7 $/\overline{5^\circ\ 30'}$

Cross-talk tests gave 40-millionths side-circuit to side-circuit and 350- to 1 700-millionths side-circuit to phantom. The a.c. capacity was 0·17 μF per naut.

A more ambitious effort is being made in connection with a new cable, now in course of construction, which will be laid next year from Dumpton Gap, near Broadstairs, to La Panne, Belgium, a distance of some 50 nautical miles. The cable will contain 7 quad cores—14 telephone loops—and will be continuously loaded with iron wire. Paper insulation is being used, and there are two lead sheaths fitted, as in the Anglo-Dutch cable. The copper is much lighter, however, the weight being 118 lb. per naut, as against 165 in the latter. The attenuation constant must not exceed 0·030 per naut and the characteristic impedance 369 $/\overline{9^\circ\ 36'}$ vector ohms (ω = 5 000 radians per sec., 1 mA testing current) for the loop circuits, and 0·036 and 148 $/\overline{10^\circ\ 9'}$ for the phantoms. The overall diameter is 2·58 in. and the weight per nautical mile 26·5 tons.

The comparatively small inductance—from 10 to 20 per naut obtained by continuously loading the copper with iron wire on the Krarup principle—limits its effect in increasing the distance over which speech is possible, especially if the pairs are squeezed up close to increase their number, since the capacity is relatively increased.

It had been known for some time that the German Administration was very anxious for a direct telephone cable to this country, but the distance, some 285 miles, with light Krarup loading appears to be prohibitive. Two lengths of approximately 9 nautical miles each of coil-loaded, paper-insulated lead-covered cable, were this year manufactured by two German firms, each length containing 7 quads, with seven loading points spaced about 1¼ nauts apart. The 14 coils serving the 14 telephone loops were spread inside a "blob" 12 ft. long in one case and 15·75 ft. in the other, the largest diameter being 4·72 inches in the first and 5·5 inches in the second cable. The inductance per coil reached about 40 mH, with an a.c. resistance (at a frequency of 5 000 radians per second) of from 3 to 4 ohms. The effect of the additional inductance gave an attenuation constant of 0·01465 for No. 1 cable and 0·01484 for No. 2 cable, and a characteristic impedance of 615 ohms for the first and 570 ohms for the second. The copper conductors in No. 1 cable were 164·5, and in No. 2, 218 lb. per naut. The trials on these cables, which were made before laying, in position and after recovery, were carried out in the North Sea on the 27th–30th July, by the Reichpost authorities and were quite successful, apart from a fault developing in each length; neither fault, however, was of a very serious nature. These trials show that: (1) A cable of this type appears to maintain satisfactorily during laying and recovery the circuit electrical characteristics as regards transmission efficiency, distortion and freedom from inductive disturbance; (2) a cable of this type can be laid and recovered satisfactorily, provided the sea bottom is not too deeply sanded, by a cable-ship properly equipped for the purpose. The provision of a direct telephone cable from England to Germany is therefore a problem which awaits financial and traffic considerations only.

PERMISSIBLE CURRENT LOADING OF BRITISH STANDARD IMPREGNATED PAPER-INSULATED ELECTRIC CABLES.

SUPPLEMENT TO SECOND REPORT (REF. F/T12)* ON THE RESEARCH ON THE HEATING OF BURIED CABLES.

[REPORT (REF. F/T15) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

APPENDIX X.

Calculation of the Temperature-Rise of Electric Cables Buried in Groups.

In Technical Report Ref. F/T12 it was shown by Messrs. S. W. Melsom and H. C. Booth that the heating of cables buried in a group in the same horizontal plane, so that each influences the temperature-rise of the others, may be calculated by a superposition method. This is based upon a method originally suggested by Kennelly.† A general solution is now given applicable to cables buried at the same or at different depths.

The method is only an approximate one, but the accuracy of the result obtained is probably amply sufficient for the conditions encountered in practice. In view of the local variations in the moisture content of the soil, it is impracticable to estimate the heating of a single cable over its whole length with a high degree of accuracy, and therefore the approximate method described herein is justified when dealing with the more complicated subject of grouped cables. When it is necessary to determine the heating of grouped cables with great accuracy, it will be found more advantageous to give attention to the nature and condition of the soil than to further elaboration of the calculations.

The superposition method may be briefly stated thus: It is found experimentally that the temperature-rise of each cable may be determined by adding to the rise proper of the cable taken singly the temperature-rises which would be caused at the point where it is situated by each of the several neighbouring cables taken separately.

Referring to Fig. 1, it is then necessary to calculate the temperature-rise t_x at any point P at which a cable may be situated due to any other cable A, the depths and horizontal distance between the centres being as indicated in Fig. 1.

The temperature-rise t_4 at the surface of cable A (i.e. at radius r_6) is first ascertained by the method shown in Technical Report Ref. F/T12.‡ The temperature-rise t_x may then be calculated by the following formula,§ which is the general solution applicable to cables buried at the same or at different depths, referred to above :—

$$\frac{t_x}{t_4} = \frac{\log \dfrac{(L + L_1)^2 + x^2}{(L - L_1)^2 + x^2}}{2 \log \dfrac{2L}{r_6}}$$

* See *Journal I.E.E.*, 1923, vol. 61, p. 517.

† *Electrical World*, 1893, vol. 22, p. 183.

‡ For convenience the values of the thermal resistance S of the cable per cm length required in this calculation have been computed and issued in this supplement, for all the British Standard cables referred to in Ref. F/T12.

§ For proof of this formula see page 164.

The temperature-rise t_x is to be added to that proper to the cable at P, and if there are other neighbouring cables the temperature-rise due to each must be calculated and superposed in a similar manner. It is important to note that the temperature-rises to be taken in making the above calculation are those due to each cable taken singly as though laid alone, and not the higher values which result from the influence of neighbouring cables.

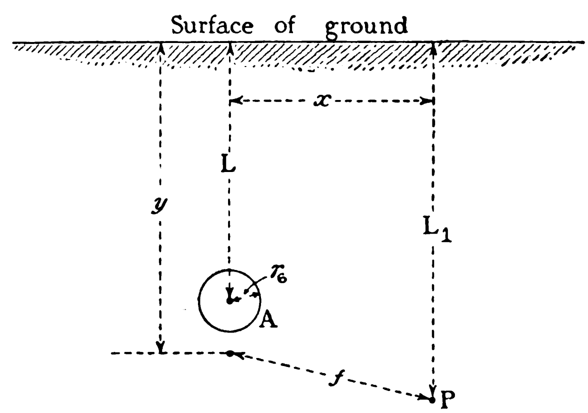


Fig. 1.

P = Point where a cable is situated, the temperature-rise of which is affected by a neighbouring cable A.
A = Cable causing temperature-rise at P.
L = Depth to centre of cable A, in inches.
L_1 = Depth of point P, in inches.
x = Horizontal distance between A and P, in inches.
r_6 = Radius of outer surface of cable A, in inches.
f = Radius of isothermal passing through point P, in inches.
y = Depth below surface of ground of centre of isothermal passing through point P, in inches.
t_4 = Temperature of outer surface of cable A.
t_x = Temperature-rise at point P due to A.

$$\frac{t_x}{t_4} = \frac{\log \dfrac{(L + L_1)^2 + x^2}{(L - L_1)^2 + x^2}}{2 \log \dfrac{2L}{r_6}}$$

Use of curves.

The estimation of t_x from t_4 may generally be made with sufficient accuracy by the use of the curves in Fig. 2. These are not derived from the formula given above but are based on the assumption of concentric isothermals. In Fig. 2, d is the radial distance from

the centre of cable A to the centre of the cable at P (Fig. 1). In most practical cases the values derived from the curves will agree with those derived from the formula to within $\pm$ 10 per cent.

The methods represented above are based on the work of Messrs. C. E. R. Bruce, W. P. Fuller, W. Bevan Whitney and the Director of Research.

Equating the two expressions for f^2 we obtain—

$$y = \frac{x^2 + L^2 + L_1^2}{2L_1}$$

hence by (39)—

$$\frac{B^2 + 1}{B^2 - 1} = \frac{x^2 + L^2 + L_1^2}{2LL_1}$$

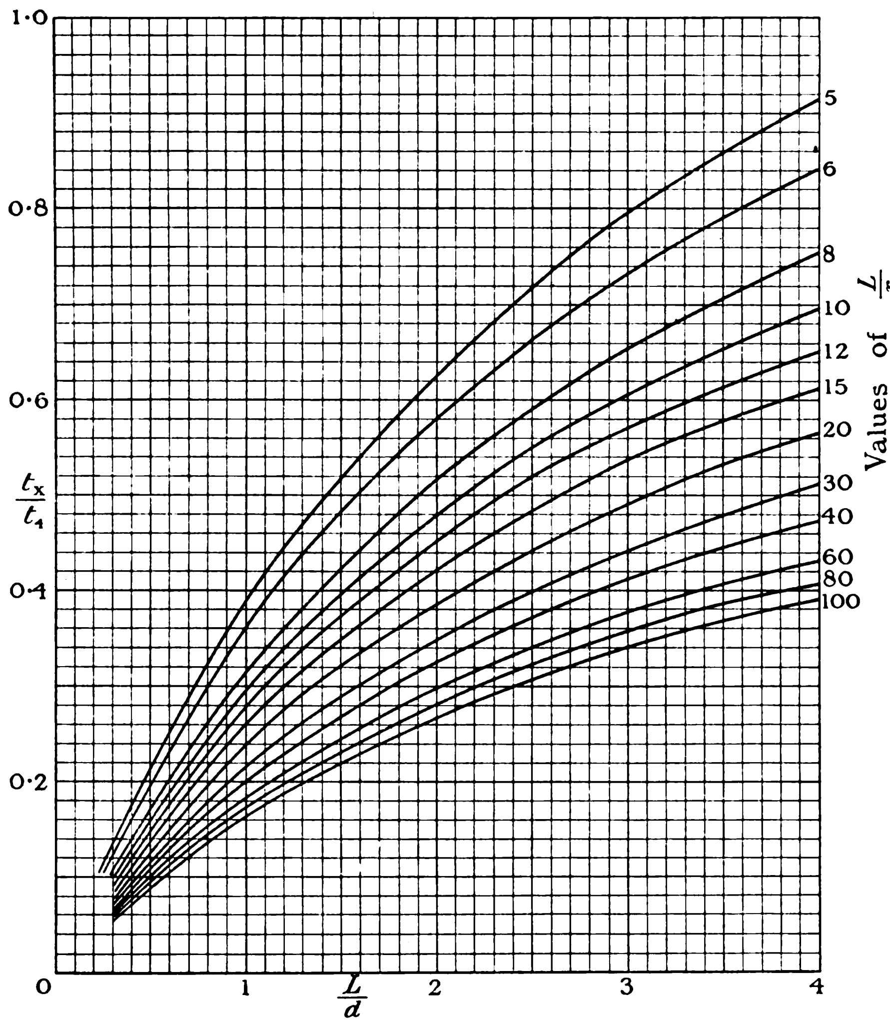


FIG. 2.—Curves for the evaluation of t_x.

Mathematical proof of the formula given on page 161.

Starting with the formulæ (39), (40), (41) in Technical Report Ref. F/T12 we have from (40)—

$$f^2 = \frac{4L^2B^2}{(B^2 - 1)^2}$$

$$= L^2 \frac{(B^2 + 1)^2 - (B^2 - 1)^2}{(B^2 - 1)^2}$$

substituting for y from (39)—

$$= y^2 - L^2$$

also $$f^2 = L_1^2 - 2L_1y + y^2 + x^2$$

or $$B^2 = \frac{x^2 + (L + L_1)^2}{x^2 + (L - L_1)^2}$$

Hence $$B = \sqrt{\left(\frac{(L + L_1)^2 + x^2}{(L - L_1)^2 + x^2}\right)}$$

$$= [M + \sqrt{(M^2 - 1)}]^{\delta} \text{ from (41).}$$

Hence $$\delta = \frac{\log B}{\log [M + \sqrt{(M^2 - 1)}]}$$

$$= \frac{\log \dfrac{(L + L_1)^2 + x^2}{(L - L_1)^2 + x^2}}{2 \log [M + \sqrt{(M^2 - 1)}]}$$

or taking the approximate value $2M$ for $M + \sqrt{(M^2 - 1)}$ and remembering that

$$M = \frac{L}{r_6}$$

we obtain
$$\delta = \frac{\log \dfrac{(L + L_1)^2 + x^2}{(L - L_1)^2 + x^2}}{2 \log (2M)}$$

Notes on the superposition method.

At first sight it would appear that the method of superposition cannot be correct, as in fact under working conditions the cables influencing each other are both loaded and therefore both running above the temperature taken in the calculation. It might be supposed that after evaluating the extra temperature-rise due to proximity by the formulæ given, the newly corrected figures should be used again for a closer approximation. This is not so, and if it were done it would be found that each successive approximation so made would give an increasingly higher result and without limit.

Examination of the basis of the formulæ employed shows that they are correct only provided that the cables be either mathematical points or material having the same thermal resistivity as the surrounding soil. If a cable were surrounded by a continuous ring of cables of infinitely high thermal resistance the heat could not escape at all and the temperature-rise would be unlimited, even though the surrounding cables carried no load. In a typical case, however, in which there are, say, two cables 2 in. diameter laid 10 in. apart, it will be seen that at the radius of 10 in. each cable occupies less than one-thirtieth of the cross-section of soil through which the heat of the other cable is escaping, and thus can have but a negligible influence whatever its thermal resistivity may be.

Under working conditions the thermal resistivity of one cable considered as part of the path of heat-flow from another cable is not greatly different from that of the surrounding soil, its dielectric of relatively high resistivity being surrounded by lead or armouring of relatively low resistivity, and doubtless in many cases its presence would actually improve the conditions.

It is not easy to picture how it is that the superposition principle can apply to several hot cables near together and with the dissipation of their heat taking place along the same path, but a rough calculation of an extreme case which admits of ready solution may be reassuring.

Let there be two cables represented by solid copper rods of relatively high thermal conductivity, of the same diameter and equally loaded. Now if these be brought nearer and nearer together it might be thought the superposition principle would give too low a value in an increasing degree. Take then the extreme case and assume the two rods can be superposed. They now occupy the same space and have to share the surrounding soil which now carries twice the heat-flow that it did before. This then results in doubling the temperature-rise, but the superposition principle gives precisely this answer. In actual practice ignoring any drying effect on the soil, the superposition method would give results erring on the high side for copper rods in near proximity, as their presence in the soil would improve the general conductivity.

APPENDIX XI.

Thermal Resistance of British Standard Impregnated Paper-Insulated Armoured Cables.

In Technical Report Ref. F/T12, it is shown that the heat emission of a cable can be deduced from the following formula :—

$$H = t/(S + G)$$

From the information given in Ref. F/T12, G can be computed without difficulty, but the value of S varies with the type and size of the cable under consideration.

The values of the thermal resistance per cm length, S, of the impregnated paper-insulated armoured cables given in British Standard Specification No. 7 have been computed by Messrs. S. W. Melsom and H. C. Booth and are shown below.

By the insertion of the appropriate value of S in the formula given above, an engineer is enabled to compute the temperature which will be reached in a British standard cable under service loading conditions for any method of laying and in any kind of soil.

Area of conductor, sq. in.	Single-core cables for 660 volts	Thermal resistance, S, per cm length of cable (see Ref. F/T12)																					
		Concentric cables											Three-core cables (circular conductors)										
		Working pressure, volts											Working pressure, volts										
		660	2 200		3 300		5 500		6 600		11 000		660	2 200		3 300		5 500		6 600		11 000	
			a	b	a	b	a	b	a	b	a	b		a	b	a	b	a	b	a	b	a	b
0·007	216	207	—	—	—	—	—	—	—	—	—	—	146	—	—	—	—	—	—	—	—	—	—
0·01	207	174	—	—	—	—	—	—	—	—	—	—	123	—	—	—	—	—	—	—	—	—	—
0·0145	149	145	—	—	—	—	—	—	—	—	—	—	108	—	—	—	—	—	—	—	—	—	—
0·0225	121	118	146	130	119	107	130	110	135	114	153	122	93	105	98	89	81	94	88	96	92	108	95
0·03	105	103	128	114	106	96	117	98	121	103	140	110	83	95	88	80	75	85	79	88	78	98	86
0·04	92	94	114	101	96	85	104	88	108	92	130	100	74	85	79	71	67	77	71	80	72	88	78
0·06	75	81	96	85	81	72	89	75	94	78	107	85	64	72	68	62	59	66	63	68	63	76	69
0·075	69	75	90	80	77	69	85	71	88	74	103	83	60	69	65	59	56	63	59	66	60	73	66
0·1	63	69	83	74	71	64	79	66	82	69	95	75	57	64	61	54	53	59	54	61	57	69	62
0·12	60	66	—	—	—	—	—	—	—	—	—	—	54	—	—	—	—	—	—	—	—	—	—
0·15	62	62	75	65	64	57	70	60	75	62	87	69	51	59	55	50	48	53	51	55	52	63	57
0·2	56	56	68	60	59	53	66	55	69	57	82	64	47	54	52	46	45	51	46	52	49	59	54
0·25	54	55	62	56	54	50	62	51	64	54	77	59	46	52	47	44	43	48	46	49	47	56	51
0·3	51	51	—	—	—	—	—	—	—	—	—	—	44	—	—	—	—	—	—	—	—	—	—
0·4	48	50	—	—	—	—	—	—	—	—	—	—	42	—	—	—	—	—	—	—	—	—	—
0·5	46	45	—	—	—	—	—	—	—	—	—	—	39	—	—	—	—	—	—	—	—	—	—
0·6	42	42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0·75	40	41	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1·00	36	36	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

a = with outer conductor or centre point *not* earthed.
b = with outer conductor or centre point earthed.
N.B.—In the three-core cable $S = fS_1 + S_2$, where f = the correction factor deduced from Fig. 36 of Ref. F/T12.

TENTATIVE DIRECTIONS FOR THE DETERMINATION OF THE ELECTRIC STRENGTH OF SOLID DIELECTRICS.*

[REPORT (REF. L/S2) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

CONTENTS—*continued.*

PREFACE.

Since the publication (see *Journal I.E.E.*, 1922, vol. 60, p. 794), of its "Directions for Determining the Electric Strength of Fibrous Insulating Materials," Ref. A/S2, the Association has had under consideration the extension of these directions to other classes of solid dielectrics. It is now generally known that the results obtained in electric strength tests of solid dielectrics depend largely on the method of test employed. If different observers are to obtain strictly comparative results on insulating materials, it is essential that the method of test employed be standardized.

The standardization of a method of test which shall be applicable to formed and moulded pieces as well as to sheet material has presented many difficulties and further experimental investigation is required before the methods herein recommended can be extended to cover all classes of solid dielectrics. Sufficient progress has, however, been made to enable the Association to issue directions in a form specifying methods for the determination of the electric strength of the various classes of commercial insulating materials which are now under examination and which cover a wide and important field.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

The researches undertaken preparatory to the preparation of this document have thrown much new light on the subject and will shortly be made the subject of a technical report. Further work is required to obtain an explanation of the results obtained which may lead to the development of new and improved methods of testing. The recommendations herein are therefore tentative and subject to revision.

It should be specially noted that the directions contained in this publication are intended to apply to tests to destruction and are not therefore applicable to tests on finished machines, as for such tests precautions would have to be taken to avoid accidental damage to the apparatus under test.

It is hoped also that the issue of the directions in this manner will prompt members and others to furnish comments on the methods suggested, and the Director will be pleased to hear from anyone who may have occasion to use them.

Part I. RESEARCH TESTS ON ELECTRIC STRENGTH.

The following methods for the determination of the electric strength are recommended when the characteristics of the material are not known, and when a thorough investigation is required to ascertain the electric strength of the material under probable service conditions.

1. General.

It is of primary importance in the case of insulating materials that the recognized electric strength be that of the material when hot and under long-continued stress.

It is desirable to test materials at temperatures appreciably above their intended working temperature.

2. Forms in which the Material may be Tested.

The directions given in this document for the study of electric strength of dielectrics provide for the specimens being in one of the following forms :—*

(*a*) Flat sheets and boards.
(*b*) Small tubes.
(*c*) Large tubes.
(*d*) Insulation built up on conductors.
(*e*) Moulded compositions.

3. Preparation of Material Previous to Test.

The ability of a material to withstand a damp atmosphere may be due to :—

(*a*) The material itself being non-absorptive.
(*b*) Additional protection given by a surface layer either developed during manufacture or added subsequently.

In the latter case the specimens shall be prepared for test in the following manner :—

(i) When the specimen is in the final form in which it will be used commercially, the protective surface layers of (*b*) above shall be retained.

(ii) When determining the properties of the material itself it is necessary to exclude the additional protection afforded by the natural layer, by making tests upon sections cut from the material having the surface layers removed at all points.

The results should state in each case how the specimen had been prepared for test.

4. Conditioning the Material Previous to Test.

As the electric strength of most insulating materials is largely influenced by their moisture content, it is desirable that the characteristic curves referred to later should be obtained for as many as possible of the conditions indicated for the class of dielectric under investigation (see Appendix I).

When a specimen is moved to an atmosphere of different relative humidity or different temperature, change of moisture content may take place very rapidly. It is, therefore, essential that the electric strength test should be made as soon as possible after the specimen has been removed from the conditioning chamber.

When it is necessary to curtail the number of tests, preference should be given to those which will give the lowest electric strength with due regard to the purposes for which the material may be used. In such cases the abridged tests given in Part II shall be employed.

5. Method of Heating or Cooling the Specimen After Conditioning and Previous to Carrying Out the Electric Strength Test.

(*a*) *Tests in Air.*

When it is desired to carry out the electric strength test at a different temperature from that at which the specimen has been conditioned the following method shall be employed.

Previous to the removal of the specimen from the conditioning chamber the test chamber and two blocks of hard brass each **3** inches diameter by 1 inch thick shall be brought to the temperature at which it is desired to determine the electric strength, also the top electrode specified in Clause 13.

The specimen shall be rapidly transferred from the conditioning chamber to the test chamber, where it shall be immediately placed between the brass blocks for the period stated in Appendix II.

At the expiration of this period the upper brass block shall be removed and the top electrode specified in Clause 13 substituted. The bottom brass block shall be retained as the bottom electrode, and the electric stress applied as soon as possible after changing the top block.

After conditioning the specimen must not be exposed, except momentarily, to either the air of the laboratory or the air of the test chamber, as this may largely eliminate the effect of the conditioning.

(*b*) *Tests in Oil.*

When the test is made in oil the latter may retard change of moisture content of the specimen during the time its temperature is being brought to that required for the electric strength test. In this case, therefore, the electric strength is not so liable to be influenced by the period which elapses between the removal of the specimen from the conditioning chamber and the application of electric stress. Previous to the removal of the specimen from the conditioning chamber, the electrodes specified

* Methods of tests for compounds normally solid at room temperature, but liquid when hot, are under consideration.

in Clause 13 and the oil bath shall be brought to the temperature at which it is desired to determine the electric strength. When removed from the conditioning chamber the specimen shall be placed immediately between the electrodes and immersed in the oil bath. Electric stress shall be applied after the period specified in Appendix II.

6. Tests in Air or Oil.

It is often more convenient to immerse the sample under oil whilst the electric strength test is carried out. Under certain conditions the breakdown voltage obtained when the material is tested in oil is not the same as the breakdown voltage which would be obtained if the material were tested in air.

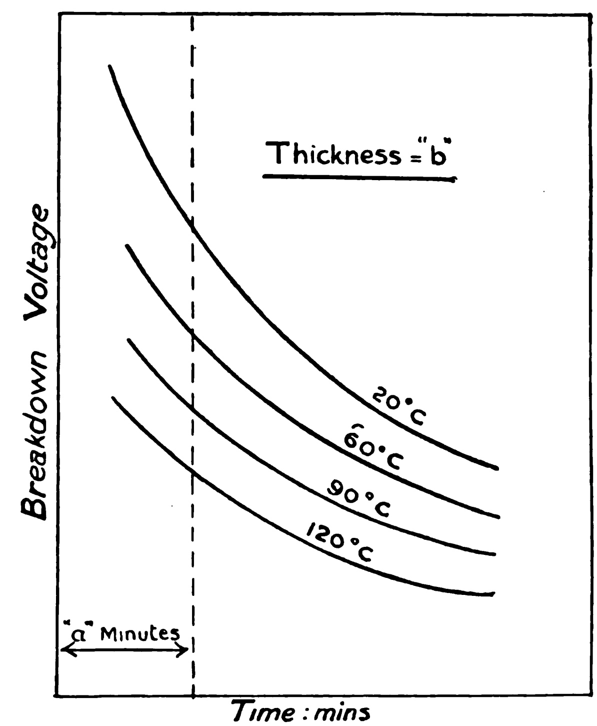


Fig. 1.—Time-voltage curves at various temperatures.

Unless the material is intended for use in oil-immersed apparatus, tests under oil are not permitted if, during the immersion under test conditions, the oil is liable to change the properties of the material in any way.

When testing materials which are intended for use in air and also in oil-immersed apparatus, it is desirable that the effect of conditioning in a damp atmosphere (Appendix I) should be ascertained both in air and in oil.

A schedule suggesting the mode of test which might be used for various classes of the more commonly employed insulating materials is given in Appendix III.

7. Method of Expressing Electric Strength.

A single value for the electric strength of most materials is misleading unless the condition of the material, the thickness, the time of application of the voltage and the temperature are either stated or clearly indicated.

Values obtained on a rapidly applied test are usually very high, being out of all proportion to the electric strength obtained by the sustained conditions of practice.

The electric strength shall be given in the form of a series of curves in which the actual breakdown voltage, R.M.S. value (0·707 of the maximum value) is plotted against time and temperature as shown in Figs. 1 and 2 respectively and in volts per mil against thickness as shown in Fig. 3.

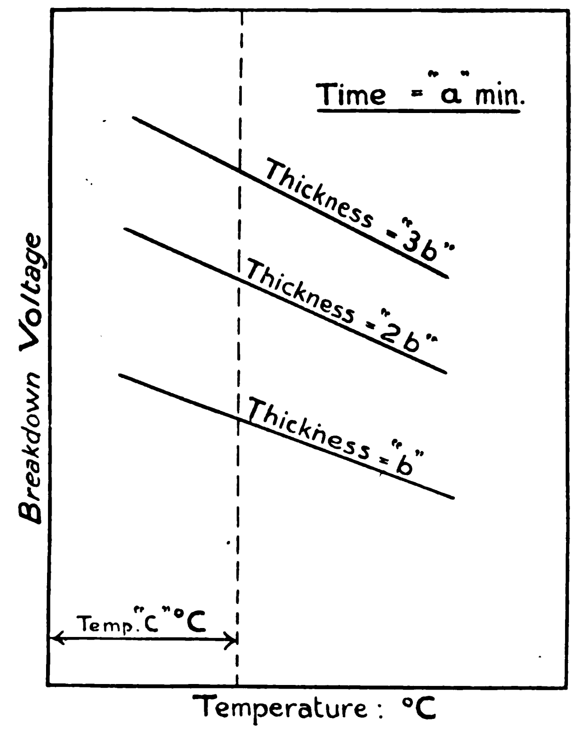


Fig. 2.—Temperature-voltage curves for various thicknesses.

Note. The temperature-voltage characteristic is not always a straight line

In calculating the electric strength in volts per mil the mean voltage gradient shall be employed, i.e. the breakdown voltage divided by the thickness of the dielectric. If in the case of tubes, or special shapes, it is desired to calculate the electric strength from the highest voltage gradient, the method given in Appendix IV may be employed.

When a spark-gap or other method for determining the peak value is used, the peak value shall be given and also the equivalent R.M.S. value (i.e. 0·707 of the peak value). [See Clause 12 (*d*).]

8. Time-Voltage Tests.

(*a*) In carrying out electric strength tests it is important to obtain time-voltage curves,* Fig. 1 showing the breakdown voltage over the time range from 0·5

* Details of an abridged method for the determination of time-voltage curves is given in Clause 10.

minute to the time * required for the breakdown voltage to become approximately independent of the time.

(*b*) In special cases transient voltage tests may be desirable.†

9. Temperature-Voltage Tests.

It is desirable that time-voltage tests (see Fig. 1) should be carried out at the temperatures indicated in Appendix III for the class of material under investigation.

For one minute and a selected number of other time values on the time-voltage curves, a temperature-voltage curve should be drawn similar to Fig. 2.

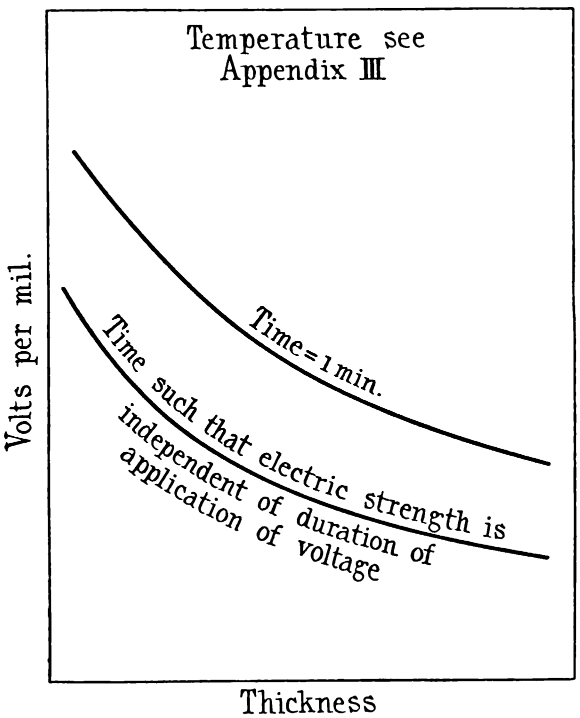


Fig. 3.—Curves showing variation of electric strength with thickness

10. Thickness-Voltage Tests.

When the material is supplied in more than one thickness it is further desirable that sufficient of the foregoing temperature-voltage curves, Fig. 2, should be obtained to enable the thickness-voltage curve to be plotted for definite time and temperature conditions, as in Fig. 3.

One of the thickness-voltage curves should be plotted from the one-minute values and another from the values obtained when the breakdown voltage is sufficiently independent of the time during which the voltage is applied (see curves in Fig. 3).

When it is desired to limit the study of these curves to one temperature, the temperature to be employed shall be the one indicated in Appendix III for the material under investigation.

To minimize the work required for the construction of a thickness-voltage curve the number of thicknesses tested may be reduced to three. Two thicknesses are not sufficient, as a knowledge of the shape of the curve is important.

Note.—In plotting thickness-voltage curves the values on the vertical axis should be in terms of volts per mil, and not in terms of breakdown voltages.

11. Calculation of Electric Strength.

(*a*) *Diagrams.*

For drawing the time-voltage curves sufficient tests shall be made to enable fair curves to be drawn over the time range under investigation.

In order that some idea may be formed of the uniformity of the material, all the experimental values are to be indicated, and when considerable variation is found, this fact should be specially mentioned.

As the temperature-voltage curves are taken from the mean curves drawn through the values obtained on the time-voltage tests, the experimental points cannot be indicated on these or on the thickness-voltage curve.

(*b*) *Measurement of Thickness.*

The thickness of the dielectric shall be measured by means of a micrometer or other suitable method.

12. Test Equipment for Power Frequency Tests.

(*a*) *Output of Testing Set.*

The output of the testing set shall be sufficient to maintain on the sample under test the necessary voltage for the maximum period required.

(*b*) *Frequency.*

The frequency of the supply voltage shall be approximately 50 cycles, and, if different, its value shall be recorded.

(*c*) *Application and Regulation of Voltage.*

It is essential that the voltage be applied without shock and in some tests, such as time-voltage tests, that the required voltage should be reached as rapidly as possible.

Methods which could be used for this purpose are given below, and their relative suitability indicated.

(i) *Separate Alternator.*

Undoubtedly the best method is to have a separate alternator for the testing transformer. When this is feasible the H.T. voltage should be controlled by means of a resistance in series with the alternator field. In cases where rapid application of a definite voltage is desired, the field rheostat should be adjusted to give the required voltage before the specimen is inserted, and after inserting the specimen the voltage should be applied by closing a switch in series with the alternator field, or by short circuiting an additional resistance temporarily added.

* When some dielectrics, such as the commonly used fibrous materials, are tested hot, the time required for the breakdown to become sufficiently independent of the time of application of the voltage may be about ten minutes. When, however, the tests are carried out at air temperature (about 20° C.) the time may be considerably longer.

† Methods for carrying out transient voltage tests are under consideration.

The generator supply must be disconnected from the testing transformer before the specimen is inserted.

(ii) *Induction Regulator.*

The use of an induction regulator designed to enable the voltage to be increased smoothly is the best method to employ when a separate alternator is not available.

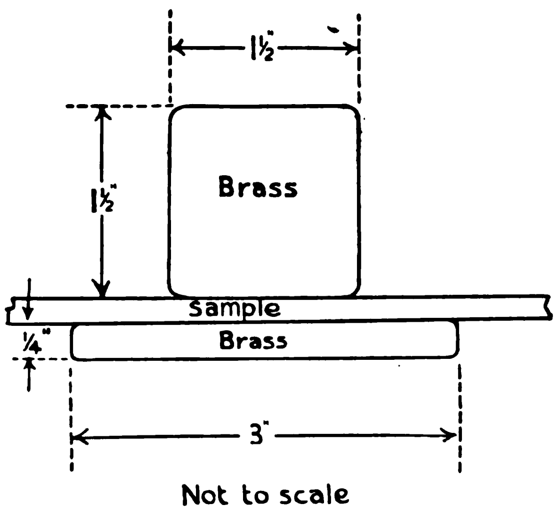


FIG. 4.—Electrodes for sheet material.

When a rapid application of a definite voltage is desired, a stop may be fixed at the required point on the regulator and the voltage applied by turning the handle rapidly from zero position to the stop.

(iii) *Tapped Transformer.*

This method does not permit the voltage to be increased smoothly and is not recommended when either method (i) or (ii) above is available. If used, the voltage between the stops should be as small as possible. This may be obtained by employing an auxiliary regulating transformer connected in series with the main regulating transformer, and having a voltage between taps of, say, 1/10 the voltage between the taps of the main regulating transformer.

When a rapid application of a definite voltage is desired, the regulator should be set to the required position and the voltage applied by closing the primary circuit through a suitable resistance, arrangements being made to short circuit the latter a fraction of a second later. The use of a three-pole switch in which one jaw is arranged to make contact slightly later than the others is a convenient way to obtain the above result.

(iv) *Series Resistance.*

An inductive or a non-inductive resistance could be inserted in series with the primary of the testing transformer. This method, although sometimes the most convenient, is not recommended, as it is liable to distort the wave shape.

If its use is unavoidable and a rapid application of the voltage is required, the same procedure as recommended in (iii) above could be used.

(*d*) *Wave Shape.*

The wave shape shall be as near sinusoidal as possible. If the wave shape is not known to be satisfactory, the peak value shall be ascertained, whilst a specimen is under test and near the point of breakdown, by means of a suitable spark-gap * or other method, and the equivalent R.M.S. value taken as 0·707 of the peak value.

(*e*) *Measurement of Voltage.*†

The voltage shall preferably be measured on the H.T. side of the testing transformer by means of a crest voltmeter, or an electro-static voltmeter. If it is desired to employ an electro-magnetic voltmeter, the instrument should derive its voltage from the H.T. circuit, either directly or through an auxiliary voltmeter transformer. If a special winding in the transformer is used to supply the voltmeter, it shall first be calibrated, when a specimen is under test and on the point of breakdown, by means of one of the other methods indicated.

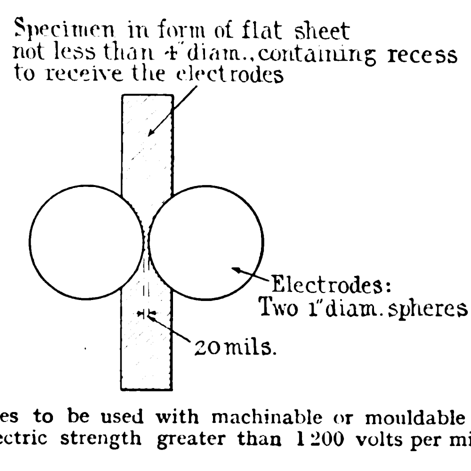


FIG. 5.—Electrodes to be used with machinable or mouldable materials having an electric strength greater than 1200 volts per mil.

* For information on suitable spark-gaps and method of use see Appendix V.

† It should be noted that the directions given in these clauses are not suitable for tests on finished machines. See fourth paragraph in Preface.

(*f*) *Prevention of H.F. Oscillation.**

The conditions of the test must be such as to prevent any H.F. oscillations. Precautions must be taken to prevent the occurrence of spark discharges in the circuit in which the specimen is being tested. When a spark-gap is used to measure the voltage a non-inductive resistance of about one ohm per volt of test pressure shall be inserted in series with the unearthed sphere. This resistance shall not be in series with the specimen under test.

A water tube is the most suitable form of resistance.

13. Electrodes.

(*a*) *For Samples in the Form of Flat Sheets or Boards.*

When the sample is in the form of a flat sheet or a board, the method of test to be employed is specified below :—

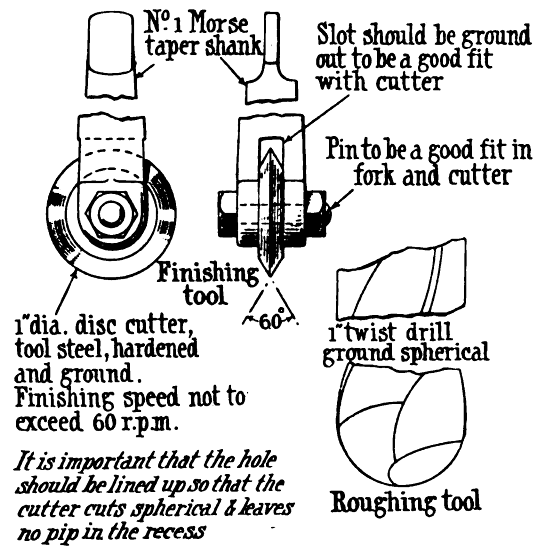


Fig. 6.—Cutter used to machine spherical recess in specimen in Fig. 5.

(i) *Machinable Materials having an Electric Strength greater than* 1 200 *volts per mil.*†

For the determination of the electric strength of high-grade ebonite and like materials, convenience and economy necessitate that the thickness of the specimen shall not be greater than 20 to 40 mils. The use of disc electrodes is therefore not practicable, and it is recommended that the electrodes employed shall consist of two spheres each 1 inch diameter,‡ arranged as shown in Fig. 5. A roughing tool and a finishing tool which have been found suitable for machining the recess for the 1 inch diameter sphere are shown in Fig. 6. When it is required to ascertain the electric strength of the interior of the sheet, the surface must be machined from the flat side of the test specimen.

* It should be noted that the directions given in these clauses are not suitable for tests on finished machines. See fourth paragraph in Preface.

† 50 kV per mm.

‡ In E.R.A. Report Ref. B/S1 the use of a recess with a diameter of 50 mm was recommended. This has now been modified to 1 inch diameter so that it may be machined in a drilling machine.

When it is desired to test a specimen with moulded surfaces proceed as in Section (*b*) below.

(ii) *Materials having an Electric Strength less than* 1 200 *volts per mil.*

The bottom electrode shall consist of a flat* disc of brass 3 inches diameter by ½ inch thick, and the top electrode of a solid cylinder of brass 1½ inches diameter by 1½ inches high.

The sharp edges shall be removed from the electrodes, but the radius at the edge must not exceed 1/32 inch (Fig. 4).

When it is desired to make electric strength tests in air at temperatures differing from room temperature, the bottom electrode shall consist of a brass block 3 inches diam. by 1 inch thick. (See Clause 5.)

(*b*) *For Compositions Moulded to Finished Shapes.*

When the sample is in the form of a moulded piece, the method of test to be employed is specified below :—

(i) *Materials having an Electric Strength greater than* 1 200 *volts per mil.*†

The specimen should be moulded to the shape shown in Fig. 5, and its electric strength determined with electrodes consisting of two spheres each 1 inch diameter. When it is required to ascertain the electric strength of the interior portions of the specimen, the surface portions must be removed by machining both the flat side and also the spherical recess. The finishing tool shown in Fig. 6 may be employed for the latter.

(ii) *Materials having an Electric Strength less than* 1 200 *volts per mil.*†

The use of specimens moulded to a special shape is not recommended for materials having an electric strength less than 1 200 volts per mil,† for the following reasons :—

Recent researches have definitely shown that in comparing one material with another the results obtained with different shapes of electrodes may vary over a very wide range: in the case of sphere versus disc electrodes, sometimes one and sometimes the other giving the higher result. The difference between the values obtained with different shapes of electrodes depends on the conditions of test, the moisture content, etc., and it has not been found possible to correlate the values obtained. It is therefore more important than has been realized in the past to employ whenever practicable the same shape of electrode for all classes of solid dielectrics.

It is recommended that in future the electric strength of mouldable materials should, whenever practicable, be determined with specimens in the form of flat sheets, thus permitting the use of the disc electrodes shown in Fig. 4.

The question of the shape of electrode which should be employed for the determination of the electric strength of porcelain is still under consideration. Recommendations will be made when the necessary experimental investigations have been completed.

* When the surface of the specimen is irregular or any difficulty is experienced in obtaining good contact, it is recommended that tinfoil should be interposed between the electrode specified and the dielectric.

† 50 kV per mm.

(*c*) *For Small Tubes* (*up to about* 3 *inches inside diameter*).

The outside electrode shall consist of a band of sheet metal 1 inch wide.

The inside electrode shall consist of a cylinder with the ends rounded to a radius of 1/8 inch, or when a cylinder with rounded ends cannot conveniently be obtained, a sheet metal * cylinder sprung into place may be employed. The length of the inside electrode shall not be less than 1 inch plus three times the thickness of the wall of the tube (see Fig. 7).

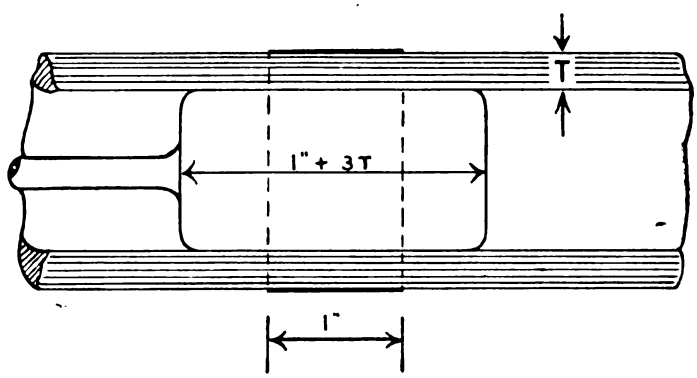


FIG. 7.—Electrodes for small tubes.

(*d*) *For Large Tubes* (*often called Cylinders*).

The outside electrode shall consist of a strip of sheet metal † 3 inches wide.

The inside electrode shall consist of a disc 1½ inches diameter of sheet metal sufficiently flexible to conform to the curvature of the cylinder: this disc of sheet metal to be pressed against the inside of the cylinder so as to make good contact over the whole of the area of the disc (Fig. 8).

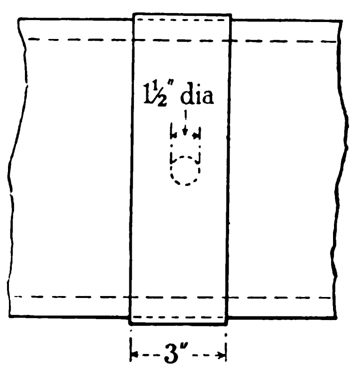


FIG. 8.—Electrodes for cylinders.

(*e*) *For Insulated Bars and Rods.*

The conductor on which the insulation is built up shall be employed as the inside electrode.

A strip of metal foil about 3 inches wide and sufficiently flexible to conform to the contour of the coil or bar shall be employed as the outer electrode, as shown in Fig. 9.

(*f*) *For Insulated Wires.*

When it is required to determine the electric strength of insulated wires the method of test to be employed is specified below:—

(i) *Wires of Overall Diameter of* 0·040 *inch and less.*

A single layer of the wire shall be evenly wound on to a smooth brass tube. The tension on the wire during winding shall be comparable with that usually employed in winding coils with wire of the size under investigation. The outside diameter of the brass tube shall be 1 inch for wires of 0·040 inch to 0·020 inch overall diameter, and ¼ inch diameter for wire of overall diameter less than 0·020 inch. The electric strength of the covering shall be determined by testing from the winding to the brass tube.

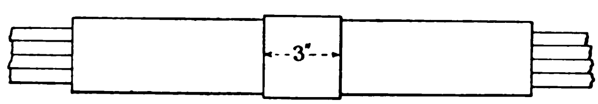


FIG. 9.—Electrode for insulation built up on conductors.

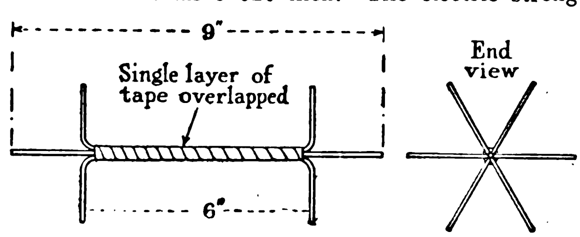


FIG. 10.—Method for large sizes of round insulated wire.

(ii) *Wires of Overall Diameter greater than* 0·040 *inch and all Sizes of Square or Rectangular Wires.*

When the conductor is circular in section, seven straight pieces shall be cut 9 inches long. Six of the lengths shall be arranged symmetrically round the seventh as core and shall be taped tightly together with one half-lapped layer of cotton tape 0·007 inch thick, for a distance of six inches, as shown in Fig. 10.

* Sheet zinc about 1/32 inch thick has been found convenient for springing into tubes for forming the inside electrode.

† Soft aluminium foil from 2 to 5 mils thick has been found convenient for use as the outside electrode on tubes.

When the conductor is square or rectangular in section seven straight wires each 9 inches long shall be laid together, as shown in Fig. 11, and taped together for a distance of 6 inches as directed above.

Previous to conditioning the ends of the wires shall be bent outwards, as shown in the end view in Figs. 10 and 11. The test shall be made between adjacent wires, and the electric strength of the insulation shall be taken as half the average value obtained by the above test, and expressed as the electric strength of one side of one wire.

(*g*) *Compounds Normally Solid at Room Temperature but Liquid when Hot.*

Methods of test for bitumens, waxes, filling compounds, etc., are under investigation, recommendations are not yet available.

General Note on the Mechanical Pressure to be exerted by the Electrodes on the Specimen.

When employed under service conditions the insulation may be required to withstand considerable mechanical pressure at the same time as it is subjected to electrical stress. Also it has been found that in the case of certain classes of dielectrics the internal heating caused by the leakage currents may volatilize

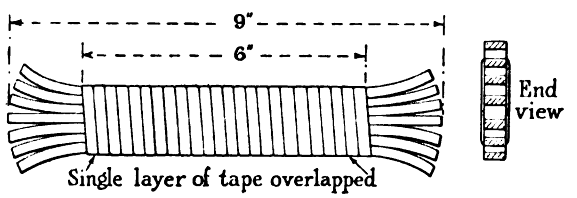


FIG. 11.—Method for square and rectangular insulated wire.

certain constituents of the dielectric and thereby cause the material to swell. As any swelling of the material between the electrodes is liable to result in an increase in the breakdown voltage, it is essential that the mechanical pressure on the electrodes should be sufficient to counteract any such tendency. When considered necessary, suitable * mechanical pressure shall be applied by means of deadweights, springs, screws, etc., to prevent any change in distance between the electrodes.

14. BREAKDOWN ALONG LAMINÆ.

Materials which are composed of a number of superimposed layers generally have a different electric strength in the direction parallel to the laminæ from that in the direction at right angles to the laminæ. All such material should, therefore, be subjected to a longitudinal breakdown test carried out as follows :—

(*a*) *Tubes.*

Cut a complete ring of axial length " *l* " and clamp " hand-tight " between flat electrodes as shown in Fig. 12. The width of material under the electrodes shall be such that the sectional area of the specimen under stress is approximately 1 square inch. In the case of large tubes three tests shall be made on each ring, the position of the areas tested being 120° apart. Various lengths of specimens shall be tested and a curve plotted showing the relationship between the average electric strength in volts per mil along the laminæ and the length of specimen. The range of lengths selected shall be such that the final result, in volts per mil, is approximately independent of the length.

All tests shall be made in oil at 90° C., and the following method employed :—

Make a trial breakdown by increasing the voltage from zero to breakdown, as rapidly as the reading on the meter will permit (approximately 5 kV per second has been used). This breakdown is not to be included in the average.

Apply to another specimen of the same length 40 per cent of the breakdown voltage found by the above method, and increase the voltage by 10 per cent

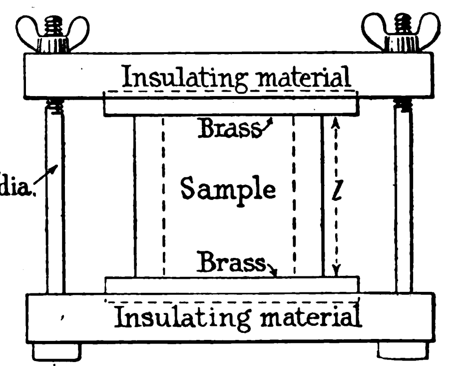


FIG. 12.—Arrangement of specimen for longitudinal breakdown test.

steps (i.e. to 50 per cent, 60 per cent, 70 per cent, etc., of the rapidly applied breakdown) at one-minute intervals till breakdown occurs. At least five determinations on each length shall be used to calculate the average, and the maximum, minimum and individual values shall also be recorded.

(*b*) *Sheet Material.*

Cut strips of various widths and of any convenient length. Test singly in a manner similar to Tubes (*a*) above.

15. ELECTRIC STRENGTH OF MATERIALS WHEN SUBJECTED TO LONG APPLICATION OF A.C. STRESS AT POWER FREQUENCIES AND UNDER SERVICE CONDITIONS.

Insulating material when in an electrical machine has not the same freedom to dissipate heat and moisture, and consequently will not withstand as high a stress as when subjected to an electric strength test as heretofore commonly applied. Such tests give a measure of the relative value of the different materials, but under the working conditions above described the material will not show the high strength so observed. It is, therefore, desirable to determine the maximum stress which the material will withstand when subjected

* In the case of tests on vulcanized fibre a pressure of 75 lb. weight on the 1¼ inch diameter electrode, Fig. 4, was employed. In general a weight of 50 lb. should be sufficient.

to long application of A.C. stress under such conditions as are comparable with these likely to be experienced in service.

The method for carrying out a sustained voltage test recommended by the Association in its previous Technical Publication Ref. A/S2 * is at present receiving further consideration with a view to rendering the test more suitable for standardization. The experimental investigations involved are not sufficiently advanced to enable recommendations to be included in the present tentative issue of the directions.

16. Tests at Radio Frequency.

Due to the high dielectric loss at high frequencies the breakdown voltage of insulating materials at radio frequencies is lower than at power frequencies. When a dielectric is overstressed at high frequencies the heating resulting from the dielectric loss is often of such magnitude as to render the material incapable of functioning as an insulator. Loss of insulating properties at radio frequencies may therefore occur without any evidence of a definite puncture, such as usually occurs when breakdown voltage tests are made at power frequencies. Due to the absence of any sharp point of failure, breakdown voltage tests at high frequencies are of but limited value.

Tests carried out by the American Bureau of Standards † have shown that due to the indefinite nature of radio frequency high voltage breakdowns the most satisfactory way at present known of comparing numerically the insulating properties of materials at radio frequencies is by a determination of their power factor and permittivity at radio frequencies. Based on the work of the Bureau of Standards, the American Society for Testing Materials has issued provisional specifications ‡ for high frequency tests. The E.R.A. in one of its researches is experimenting with the methods suggested by the A.S.T.M., and, whilst this research is not complete, certain changes in the methods have been found desirable and tentative recommendations are given in Appendix VII of the present publication.

Part II. ABRIDGED TESTS ON ELECTRIC STRENGTH.

The following methods for the determination of the electric strength of insulating materials are recommended when it is not required to ascertain the characteristics of the material in such detail as provided for in Part I.

17. Conditioning.

(*a*) Prior to test the materials shall be exposed to the "Normal" atmosphere as specified in Appendix I.

* *Journal I.E.E.*, 1922, vol. 60, p. 794.
† See Bureau of Standards Scientific Paper No. 471.
‡ See A.S.T.M. Publications D 150-23 T and D 175-23 T.

(*b*) If it is claimed that the material has special non-absorptive properties, it shall also be tested after exposure to either "Damp," "Tropical" or "Immersed" conditions, as specified in Appendix I.

(*c*) If it is claimed that the material has special heat-resisting properties, it shall also be tested after exposure to very dry conditions, as specified in Appendix I.

18. Method of Expressing Electric Strength.

The recognized method of expressing the electric strength of materials subjected to these abridged tests shall be the voltage required to produce breakdown in one minute when the material is tested at its appropriate temperature, as given in Appendix III. For ease of comparison the volts per mil, followed by a statement of the thickness to which it refers, shall also be given.

19. Methods for Obtaining the One-Minute Value.

To reduce to a minimum the work required to ascertain, with reasonable accuracy, the one-minute breakdown value, the following method of procedure is recommended:

(*a*) *Breakdown through the Thickness of the Material.*

Make a trial breakdown by increasing the voltage from zero to breakdown, as rapidly as is consistent with obtaining satisfactory readings of the measuring instrument (approximately 5 kV per second has been used).

Subject the material to two-thirds the breakdown voltage obtained by the above method and note the time required to produce breakdown.

From the results of this test an approximate idea can be obtained of the voltage which will produce breakdown in about one minute; this estimated voltage should then be applied and the time required to produce breakdown noted. From this latter result a still closer approximation can be made. In addition to the trial test, at least five breakdowns should be obtained on each sample, and the values plotted on a time-voltage curve, similar to Fig. 1, but for the time range round one minute only. From this curve the voltage required to produce breakdown in one minute can be determined.

(*b*) *Breakdown along Laminæ.*

Employ the one-minute 10 per cent step-by-step method as specified in Clause 14 of Part I of this document. Only one length of specimen shall be tested, the length to be employed for this test depends on the class of material and will be specified in the directions issued for the study of the particular class of material under test.

20. Other Factors.

In conducting the abridged tests for electric strength the conditions specified for the other factors entering into electric strength tests, such as electrodes, etc., are to be the same as for the research tests dealt with in Part I.

APPENDIX I.

DETAILS OF TEMPERATURE, TIME AND HUMIDITY TO BE USED FOR CONDITIONING THE CLASSES OF DIELECTRICS REFERRED TO, PREVIOUS TO THE DETERMINATION OF THEIR ELECTRIC STRENGTH.

Condition	Class of dielectric	Temp. ° C.	Time, hours	Humidity (relative) * per cent	Sp. Gr. of $CaCl_2$ † required to give the stated humidity at the stated temp.
Normal	B.E.S.A. Class O and A..	15–25	18–24	75 ‡	1·22 at 15° C.
	B.E.S.A. Class B ..	15–25	18–24	75 ‡	1·22 at 15° C.
	B.E.S.A. Class C	15–25	18–24	75 ‡	1·22 at 15° C.
	Unclassified	15–25	18–24	75 ‡	1·22 at 15° C.
Very dry	—	120–130	18–24	§	—
Dry	Treated papers and fabrics	75–80	2–3	§	—
	Other B.E.S.A. Class O and A materials	75–80	18–24	§	—
	B.E.S.A. Class B	75–80	18–24	§	—
	B.E.S.A. Class C	75–80	18–24	§	—
	Unclassified	75–80	18–24	§	—
Damp	B.E.S.A. Class O and A..	15–25	18–24	Approximately 95	Water only
	B.E.S.A. Class B.. ..	15–25	18–24	Approximately 95	Water only
	Unclassified	15–25	18–24	Approximately 95	Water only
Tropical	B.E.S.A. Class O and A .. B.E.S.A. Class B .. Unclassified	45–50 during the day (8 hours) and 15–25 during the night (16 hours)		Approximately 90 during the day. Saturated ‖ during night	Water only
Recovered	B.E.S.A. Class O and A..	75–80	8–15	§	—
		Followed by exposure to " normal " condition for one week			
¶Chemically Treated	B.E.S.A. Class C	15–25	168 (1 week)	—	—
	Unclassified	15–25	168 (1 week)	—	—

* For notes on the construction of conditioning chambers and the measurement of humidities therein, see Appendix VI.
† The use of H_2SO_4 is not recommended, as its vapour is liable to be absorbed by the specimen.
‡ This figure is adopted provisionally, awaiting recommendations from another Committee.
§ Air at ordinary room temperature and humidity is to be heated to the temperature specified, without any artificial drying or humidifying.
‖ The cubic capacity of the conditioning chamber compared with its internal area and the total area of the specimens must be such that a liberal condensation of moisture occurs on the latter during the lower temperature period.
¶ The treatment to be given will depend on the purpose for which the material is required, the following being employed :—

(i) If exposed to rain or water .. .. Distilled water.
(ii) If exposed to sea water .. .. 10 % solution of salt in distilled water.
(iii) If exposed to acid .. .. .. Sulphuric acid sp. gr. 1·25 at 15° C.
(iv) If exposed to alkalies .. .. 10 % solution of caustic soda.
(v) If exposed to ozone .. .. ..
(vi) If exposed to ultra-violet light .. Treatment to be given is under consideration.
(vii) If exposed outdoors .. .. ..

APPENDIX II.

Table I.

Periods to be allowed for bringing conditioned specimens to the temperature at which it is required to determine the electric strength when the material is to be tested in air.

Class of dielectric	Thickness	Periods for the temperature differences* indicated, during which the specimen is to be placed between 3 in. × 1 in. brass discs, previous to the electric strength test in accordance with Clause 13				
		40° C.	70° C.	100° C.	130° C.	160° C.
B.E.S.A. Class O, A and B	Not more than 1/8 in.	1 min.	1 min.	2 min.	2 min.	3 min.
B.E.S.A. Class O, A and B	>1/8 in. but not more than 1/4 in.	2 min.	3 min.	4 min.	4 min.	5 min.
B.E.S.A. Class O, A and B	>1/4 in. but not more than 1/2 in.	4 min.	6 min.	8 min.	8 min.	10 min.
B.E.S.A. Class C and unclassified	All thicknesses up to 1/2 in.	5 min.	5 min.	10 min.	10 min.	10 min.

* This refers to the difference in temperature between the conditioning and testing chambers.

Table II.

Period to be allowed for bringing conditioned specimens to the temperature at which it is required to determine the electric strength when the material is to be tested in oil.

Class of dielectric	Thickness	Periods for the temperature differences* indicated, during which the specimen is to be placed between the electrodes specified in Clause 13 previous to the electric strength test in accordance with Clause 13				
		40° C.	70° C.	100° C.	130° C.	160° C.
B.E.S.A. Class O, A and B	Not more than 1/8 in.	1 min.	2 min.	2 min.	3 min.	4 min.
B.E.S.A. Class O, A and B	>1/8 in. but not more than 1/4 in.	2 min.	4 min.	5 min.	6 min.	8 min.
B.E.S.A. Class O, A and B	>1/4 in. but not more than 1/2 in.	5 min.	8 min.	10 min	12 min.	15 min.
B.E.S.A. Class C and unclassified	All thicknesses up to 1/2 in.	5 min.	10 min.	15 min	15 min.	15 min.

Note.—The period to be employed for tests at greater differences of temperature than those referred to above is left to the discretion of the investigator.

* This refers to the difference in temperature between the conditioning and testing chambers.

APPENDIX III.

SCHEDULE OF COMMONLY-USED INSULATING MATERIALS AND PARTICULARS OF THE CONDITIONS OF TEST UNDER WHICH THEIR ELECTRIC STRENGTH SHOULD BE DETERMINED.

R = Research tests as covered by Part I of this document. | A = Abridged tests as covered by Part II of this document.

Material	Test in air at °C.									Test in oil at °C.			
	20	60	90	120	150	180	200	250	300	20	60	90	120
Class O.													
Untreated papers	R	R	RA	R	—	—	—	—	—	—	—	—	—
Untreated pressboard	R	R	RA	R	—	—	—	—	—	—	—	—	—
Untreated cotton	R	R	RA	R	—	—	—	—	—	—	—	—	—
Untreated linen	R	R	RA	R	—	—	—	—	—	—	—	—	—
Untreated natural and artificial silk	R	R	RA	R	—	—	—	—	—	—	—	—	—
Untreated soft woods	R	R	RA	R	—	—	—	—	—	—	—	—	—
Class A.													
Treated * papers	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Treated * pressboard	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Treated * cotton, linen and natural or artificial silk	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Vulcanized fibre	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Varnish-paper products	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Untreated hard woods	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Treated * soft and hard woods ..	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Mica products containing less than . . .† (by volume) of mica ..	R	R	RA	R	—	—	—	—	—	R	R	RA	R
Untreated or treated asbestos products containing more than . . .† (by weight) of ignitable matter	R	R	RA	R	—	—	—	—	—	R	R	RA	R

* Impregnated with insulating material (see British Standard Specification No. 168) or immersed in oil.
† This value is being determined by means of experimental investigation; recommendations are not yet available.

APPENDIX III (*continued*).

Material	Test in air at ° C.									Test in oil at ° C.			
	20	60	90	120	150	180	200	250	300	20	60	90	120
Class B.													
Untreated and treated asbestos products containing less than . . .* (by weight) of ignitable matter	R	—	RA†	—	RA†	R	—	—	—	R	—	RA	R
Mica products containing more than . . .* (by volume) of mica	R	—	RA†	—	RA†	R	—	—	—	R	—	RA	R
Class C.													
Block mica	R	—	RA†	—	R	—	RA†	R	R	R	—	RA	R
Porcélain §													
Glass	R	—	RA†	—	R	—	—	—	—	R	—	RA	R
Marble and slate	R	—	RA†	R	—	—	—	—	—	R	—	RA	R
Lava and steatite	R	—	RA†	—	R	—	—	—	—	R	—	RA	R
Natural and reconstructed silica..	R	—	RA†	—	R	—	RA†	R	R	R	—	RA	R
Not yet Classified.													
Ebonite and rubber products ..	R	RA	‡	—	—	—	—	—	—	R	RA	‡	—
Bituminous or natural gum products	R	R	RA	‡	—	—	—	—	—	R	R	RA	‡
Syn. resin mouldings	R	R	RA	R	‡	—	—	—	—	R	R	RA	R
Arc resisting materials	R	—	RA†	—	R	—	RA†	—	R	—	—	—	—
Gums, waxes, bitumen, etc. ..	R	R	RA	‡	4	—	—	—	—	—	—	—	—

* This value is being determined by means of experimental investigation; recommendations are not yet available.
† If the material is tested after exposure to "normal," "damp" or "tropical" conditions, the abridged electric strength tests are to be made only at 90° C. and where applicable all such 90° C. tests are to be made in oil.
‡ The maximum test temperature and maximum service temperature of moulded compositions will be governed by the grade temperature of the material determined from either mechanical or electrical considerations. Certain of these materials will be found to fall within the O, A, B, C classification, if their grade temperature is determined by an appropriate test.
§ The question of the temperatures and electrodes to be employed for the determination of the electric strength of porcelain is under investigation.

APPENDIX IV.

Method of Calculating the Electric Strength from the Maximum Voltage Gradient on the Dielectric.

(*a*) *When Concentric Cylindrical Electrodes are Employed.*

If a homogeneous dielectric is tested in the form of a tube between concentric cylindrical electrodes, the distribution of the electric stress throughout the thickness of the dielectric will be a logarithmic function of the thickness and will be greatest on the layer adjacent to the inner electrode.

Table A.

Variation of Maximum Stress to Mean Stress for Various Values of "a."

$a = \frac{\text{Outside diameter}}{\text{Inside diameter}}$	Maximum stress
3	1·82 × Mean stress
2	1·44 × Mean stress
1·5	1·23 × Mean stress
1·4	1·20 × Mean stress
1·3	1·15 × Mean stress
1·2	1·10 × Mean stress
1·1	1·045 × Mean stress
1·05	1·020 × Mean stress

Let V = the breakdown voltage
R = the radius of the outside of the tube
r = the radius of the inside of the tube

and $a = \frac{R}{r}$ or $\frac{\text{outside diameter of tube}}{\text{inside diameter of tube}}$

Then the maximum stress on the dielectric

$$= \frac{V}{r \log_e a}$$

and the mean stress $= \frac{V}{r(a-1)}$.

The relationship between the maximum stress and the mean stress for various values of "*a*" is given in Table A.

The above values for the maximum stress are only true when there is a logarithmic distribution of electric stress throughout the thickness of the tube. For various reasons it is frequently impracticable to predetermine the true electric strength by calculations on the basis of the maximum stress which would be given by the above formula.

(*b*) *When the Electrodes Consist of a 1-inch Diameter Embedded Sphere and a Flat Plate.*

In the case of a homogeneous dielectric, the relationship between the maximum stress and the mean stress is given in Table B for various thicknesses of dielectric.

Table B.

Variation of Maximum Stress to Mean Stress for Various Thicknesses of Dielectric.

Minimum thickness of specimen (Mils)	Maximum stress
20	1·03 × Mean stress
40	1·06 × Mean stress
80	1·11 × Mean stress
120	1·17 × Mean stress
160	1·22 × Mean stress
200	1·28 × Mean stress

As mentioned in the last paragraph of Section (*a*) above, the values given for the maximum stress do not always apply.

APPENDIX V.

Measurement of Voltage with Spark-Gaps.

(*a*) *General.*

If proper precautions are taken a spark-gap may be used for the determination of the peak value of the voltage wave and also for checking and calibrating voltmeters for H.V. tests.

Most of the recommendations contained in this Appendix are based on methods recommended in the Standards of the American Institute of Electrical Engineers.

(*b*) *Range of Voltage.*

For the above purposes a suitable sphere-gap shall be used for voltages above 50 kV and is preferable down to 30 kV. A needle spark-gap may be used for voltages from 10 kV to 50 kV.

(*c*) *Needle Spark-Gap.*

The needle spark-gap shall be between new sewing needles, supported axially at the ends of linear conductors, which are at least twice the length of the gap. There must be a clear space around the gap for a radius at least twice the gap length.

In the Standards of the American Institute of Electrical Engineers it is stated that the values given in Table A refer to No. 00 double long needles. As needles

are not standardized any specified size is liable to slight variation in gauge, taper, and diameter of point. The nearest English needle to the one specified by the A.I.E.E. is No. 17 double long, and this size may be satisfactorily used for the needle spark gap values given in Table A and Fig. 13.

TABLE A.

Needle-Gap Spark-over Voltages (at 25° C. and 760 mm barometer and 80 per cent relative humidity).

R.M.S. Kilovolts	Sparking distance, mm	R.M.S. Kilovolts	Sparking distance, mm
10	11·9	35	51
15	18·4	40	62
20	25·4	45	75
25	33	50	90
30	41	—	—

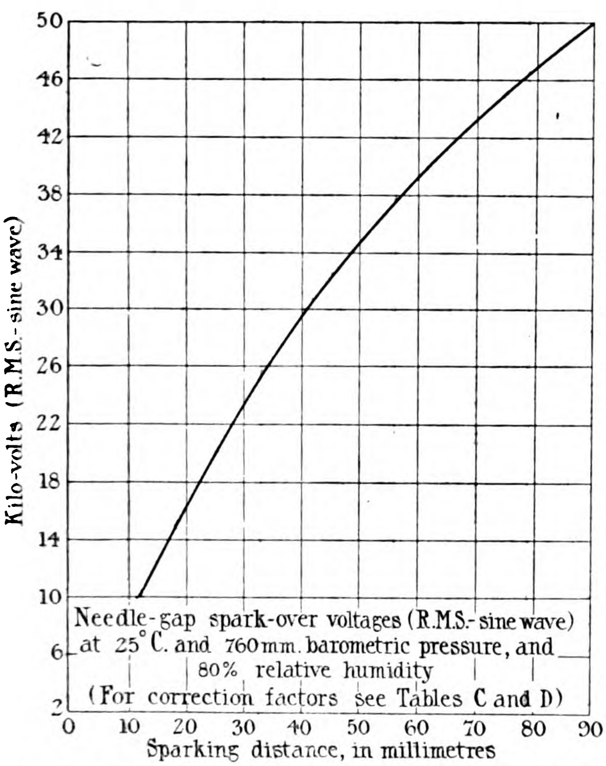


FIG. 13.—Spark-over voltages (R.M.S. sine wave) for needle-gap at 25° C., 760 mm barometric pressure, and 80 per cent relative humidity.

For accurate work it is recommended that a fresh needle be employed for each test, although there is evidence that slight burning of the points is negligible provided the distance be adjusted to compensate. This feature is the subject of further research.

The sparking distances in air between No. 17 double long sewing-needle points for various root-mean-square sinusoidal voltages shall be assumed to be as shown in Table A and Fig. 13.

(*d*) *Sphere Spark-Gap.*

The standard sphere spark-gap shall be between two suitably mounted spheres. No extraneous body, or external part of the circuit, shall be nearer the spheres than twice their diameter.

The shanks shall be not greater in diameter than 1/5th the sphere diameter. Metal collars, etc., through which the shanks extend, shall be as small as practicable and shall not, during any measurement, come closer to the sphere than the maximum gap length used in the measurement.

The apparatus shall be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap, e.g. the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

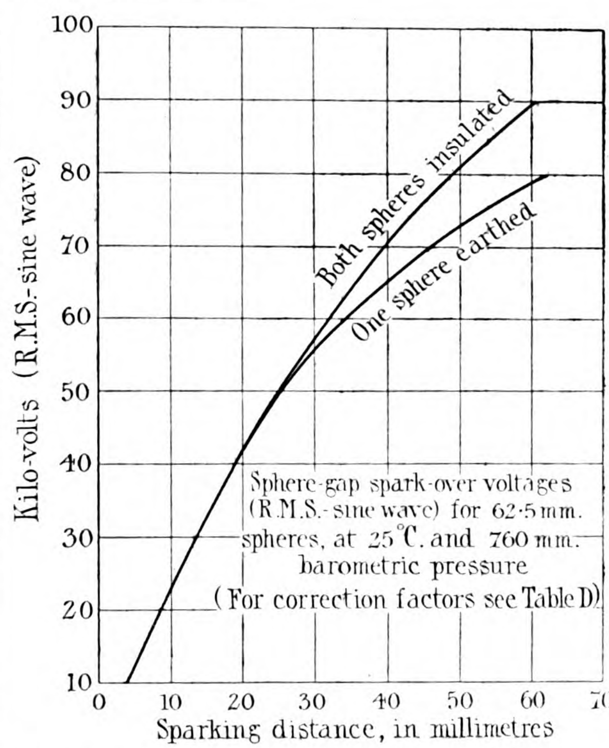


FIG. 14.—Spark-over voltages (R.M.S. sine wave) for 62·5-mm diameter spheres at 25° C. and 760 mm barometric pressure.

In case the sphere is earthed, the spark point of the earthed sphere should be approximately five diameters above the floor or ground.

The spheres shall be as truly spherical as possible.

The sparking distance between spheres for various R.M.S. sinusoidal voltages shall be assumed to be as shown in Table B and in Figs. 14 to 17 inclusive.

TABLE B.

Sphere-Gap Spark-over Voltages (at 25° C. and 760 mm barometric pressure).

Kilovolts	Sparking distance in millimetres							
	62·5-mm spheres		125-mm spheres		250-mm spheres		500-mm spheres	
	One sphere earthed	Both spheres insulated	One sphere earthed	Both spheres insulated	One sphere earthed	Both spheres insulated	One sphere earthed	Both spheres insulated
10	4·2	4·2	—	—	—	—	—	—
20	8·6	8·6	—	—	—	—	—	—
30	14·1	14·1	14·1	14·1	—	—	—	—
40	19·2	19·2	19·1	19·1	—	—	—	—
50	25·5	25·0	24·4	24·4	—	—	—	—
60	34·5	32·0	30	30·0	29	29	—	—
70	46·0	39·5	36·0	36·0	35	35	—	—
80	62·0	49·0	42·0	42·0	41	41	41	41
90	—	60·5	49·0	49·0	46	45	46	45
100	—	—	56·0	55·0	52	51	52	51
120	—	—	79·7	71·0	64	63	63	62
140	—	—	108·0	88·0	78	77	74	73
160	—	—	150·0	110·0	92	90	85	83
180	—	—	—	138·0	109	106	97	95
200	—	—	—	—	128	123	108	106
220	—	—	—	—	150	141	120	117
240	—	—	—	—	177	160	133	130
260	—	—	—	—	210	180	148	144
280	—	—	—	—	250	203	163	158
300	—	—	—	—	250	231	177	171
320	—	—	—	—	—	265	194	187
340	—	—	—	—	—	—	214	204
360	—	—	—	—	—	—	234	221
380	—	—	—	—	—	—	255	239
400	—	—	—	—	—	—	276	257

NOTE.—The sphere-gap is more sensitive than the needle-gap to momentary rises of voltage, and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap. during its operation, as they may affect its calibration.

(e) *Factors Influencing Spark-over Voltage.*

The spark-over voltage of an air-gap is influenced by the following :—

(i) *Humidity.*

The voltage required to spark across a needle-gap is influenced by the relative humidity of the air.

The values in Table A refer to a relative humidity of 80 per cent. Provided a needle-gap is not used above 30 kV, variations in relative humidity will not affect the spark-over voltage. At higher voltages the spark-over voltage for a given gap setting decreases with decrease in relative humidity.

The magnitude of the effect of change in humidity is shown in Table C and Fig. 18. This curve gives the approximate correction factor and holds for the range from about 85 per cent to 55 per cent relative humidity.

TABLE C.

Variation of Spark-over Voltage of Needle-Gap with Relative Humidity.

Spark-over voltage for 82·5 per cent relative humidity as given by Peek *	Approximate reduction in spark-over voltage at 57 per cent relative humidity. Calculated from Peek's 82·5 per cent and 57 per cent relative humidity curves *		Approximate percentage increase or decrease in spark-over voltage for each 1 per cent increase or decrease in relative humidity calculated from the spark-over voltage at 80 per cent relative humidity
	kV	Per cent	
35	0	0	0
50	1·8	3·6	0·14
60	3	5·0	0·20
70	4	5·7	0·22
80	5	6·2	0·24
100	6·7	6·7	0·26
120	8·5	7·1	0·28
140	10·5	7·5	0·30
160	13	8·1	0·31
170	14	8·2	0·32
180	16	8·9	0·35
200	20	10·0	0·40

From Fig. 18 it will be seen that the effect of each 1 per cent change in relative humidity increases with the spark-over voltage, and for this reason needle-gaps are not as accurate as sphere-gaps for voltages above about 30 kV.

Provided a sphere gap is set so that corona does not form before spark-over occurs, the spark-over voltage of a sphere-gap is independent of humidity.

(ii) *Air Density.*

The distance through which a given voltage will cause a spark to pass through air depends on the density of the air.

The spark-over voltage for a given gap thus decreases with decreasing barometric pressure and increasing temperature. This variation may be considerable at high altitudes. When the variation from sea-level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table D in which

$$\text{Relative air density} = \frac{0 \cdot 392\, b}{273 + t}$$

b = barometric pressure in mm.
t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired. It will be noted in Table D that for values of relative air density above 0·9 the correction factor does not differ greatly from the relative air density.

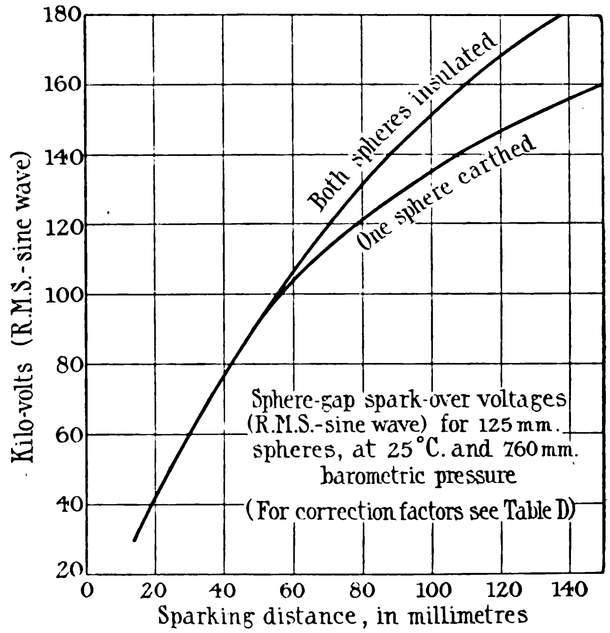


FIG. 15.—Spark-over voltages (R.M.S. sine wave) for 125-mm diameter spheres at 25° C. and 760 mm barometric pressure.

The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows: Divide the required voltage by the correction factor given in Table D and use the new voltage thus obtained to find the corresponding spacing from Table B, using a graph of the latter if more convenient.

(iii) *Other Factors.*

As an indication of the effect of other factors the following results (see Table E) reported by F. W. Peek * are given for the guidance of those using spark-gaps for the measurement of high voltages.

Marvin † has shown that cotton lint from a dry cloth

* See "Dielectric Phenomena in High Voltage Engineering," by F. W. Peek, Jr. First Edition, p. 87.

* See *General Electric Review*, June 1916, p. 564.
† See *Electrical World*, March 18, 1916.

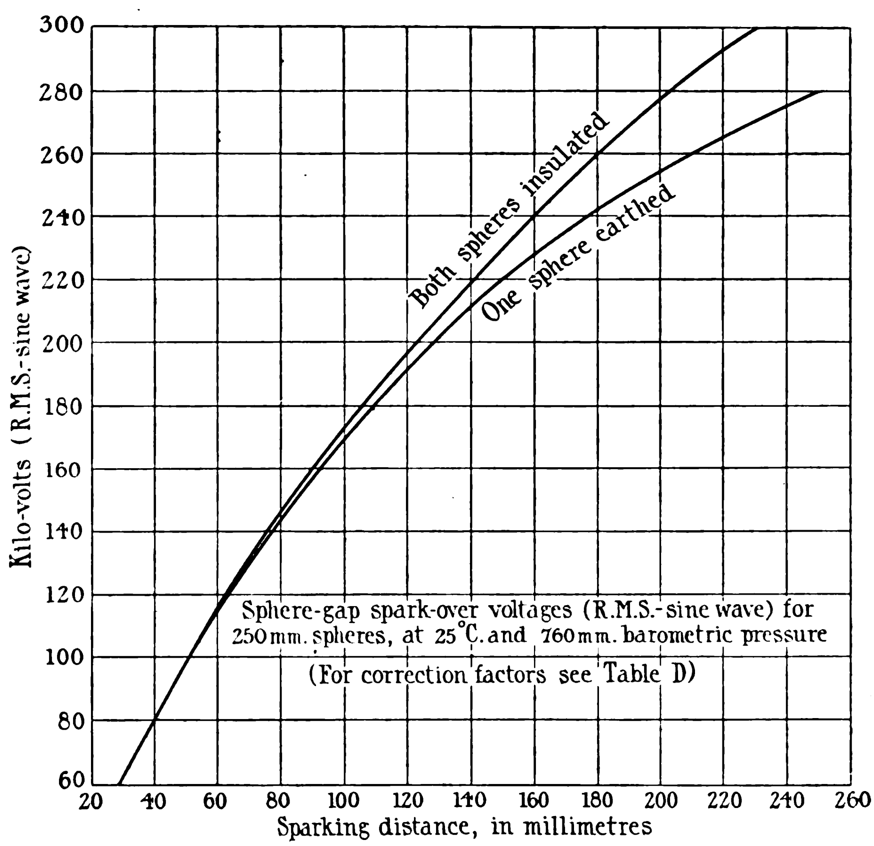


Fig. 16.—Spark-over voltages (R.M.S. sine wave) for 250-mm diameter spheres at 25° C. and 760 mm barometric pressure.

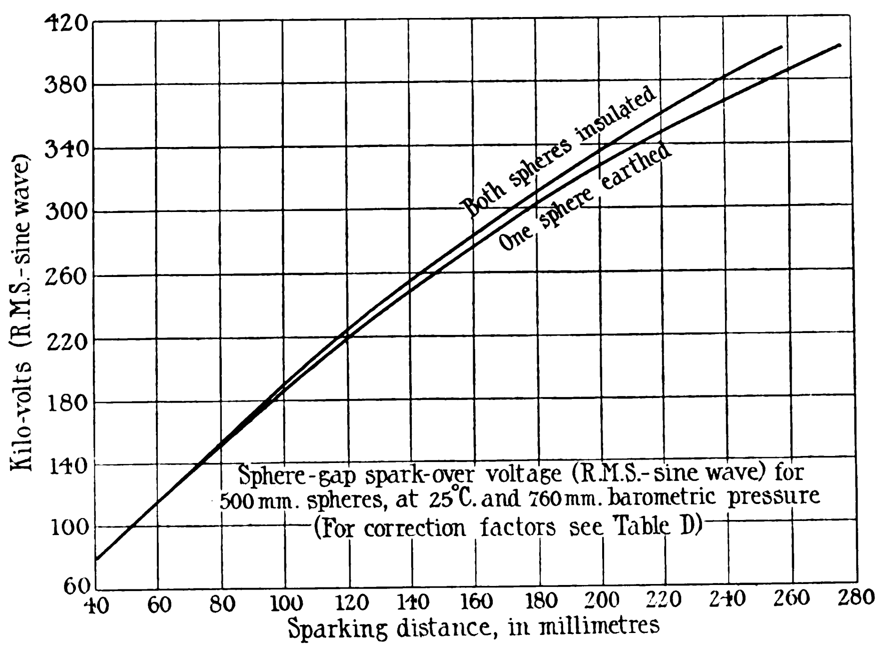


Fig. 17.—Spark-over voltages (R.M.S. sine wave) for 500-mm diameter spheres at 25° C. and 760 mm barometric pressure.

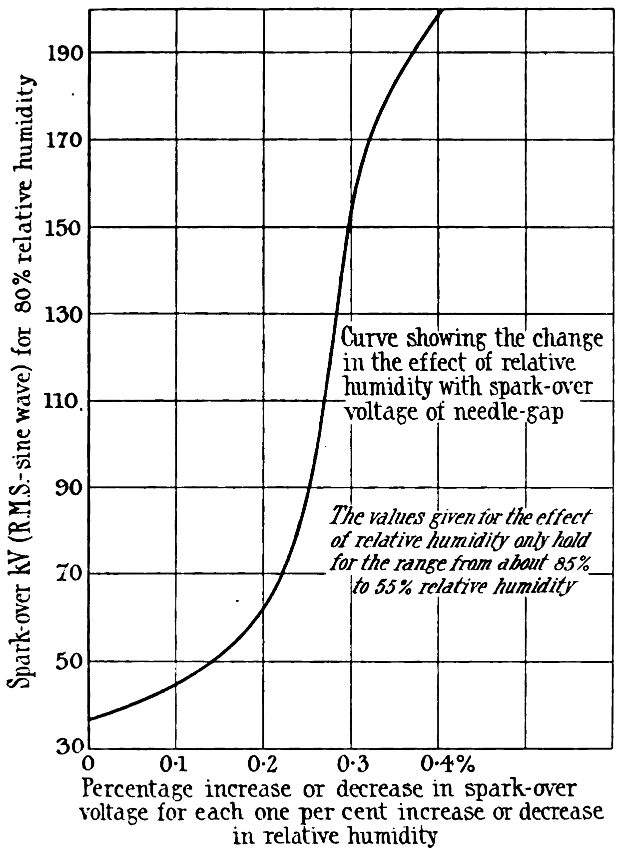


FIG. 18.

TABLE D.

Air Density Correction Factors for Sphere-Gaps.

Relative air density	Diameter of standard spheres in mm			
	62·5	125	250	500
0·50	0·547	0·535	0·527	0·519
0·55	0·594	0·583	0·575	0·567
0·60	0·640	0·630	0·623	0·615
0·65	0·686	0·677	0·670	0·663
0·70	0·732	0·724	0·718	0·711
0·75	0·777	0·771	0·766	0·759
0·80	0·821	0·816	0·812	0·807
0·85	0·866	0·862	0·859	0·855
0·90	0·910	0·908	0·906	0·904
0·95	0·956	0·955	0·954	0·952
1·00	1·000	1·000	1·000	1·000
1·05	1·044	1·045	1·046	1·048
1·10	1·090	1·092	1·094	1·096

may reduce the spark-over voltage of a 25 cm diameter sphere-gap set with gap of 123 mm to 78 per cent of normal value.

It is recommended that previous to use the spheres should be polished and wiped with a wash-leather which is slightly oily.

(*f*) *Use of Resistance in Series with Spark-Gap.*

To prevent high-frequency oscillations and to limit the current when spark-over occurs, a non-inductive resistance of about one ohm per volt of test pressure shall be inserted in series with the spark-gap. If the test is made with one electrode earthed the resistance shall be inserted directly in series with the non-earthed electrode, if neither terminal is earthed one-half shall be inserted directly in series with each electrode. In either case the resistance shall be as near the measuring gap as possible, but must be arranged so as to fulfil the condition set forth in (*d*) above.

TABLE E.

Spark-over Voltage of 12·5-cm Spheres under the Conditions Stated.

Condition of sphere	Per cent of normal spark-over voltage	
	5 cm gap	10 cm gap
Polished	100	100
Thin coating of dry dust ..	98	98
Excessive pitting (craters 0·4 mm deep and beads 0·25 mm in height)	90	75
Rain 0·2 in. ppt. per min. (polished spheres)	42	39

APPENDIX VI.

NOTES ON CONDITIONING CHAMBERS AND THEIR EQUIPMENT.

(*a*) *Construction.*

(i) *Cold Chambers.*

For conditioning or test chambers which are not required to be heated, a satisfactory and convenient method of construction is to make the chamber of 3/4-in. tongued and grooved boards and to line the inside with thin sheet metal. The latter should be soldered down all joints such as those occurring where the sides meet the top and bottom. The use of a sheet metal lining is essential when it is required to employ the chamber for very high or very low humidities.

(ii) *Hot Chambers.*

When a chamber is required for temperatures above those of the laboratory, an electrically heated oven having double walls of sheet metal with the interspace suitably packed is recommended.

(*b*) *Method for Obtaining the Specified Humidities in Cold Chambers.*

(i) *Relative Humidity of Approximately* 100 *per cent.*

Even when a large area of water is freely exposed in a chamber with walls of a non-absorptive material, it is impracticable to obtain a relative humidity exceeding 95 per cent. It has been found, however, that if a constant current of air be made to pass over the surface of the exposed water and the air in the chamber be kept continually stirred there is no difficulty in obtaining a relative humidity of 96 to 98 %. A simple method which has been used for obtaining this high humidity is shown in Fig. 19. Unless the conditioning chamber is really

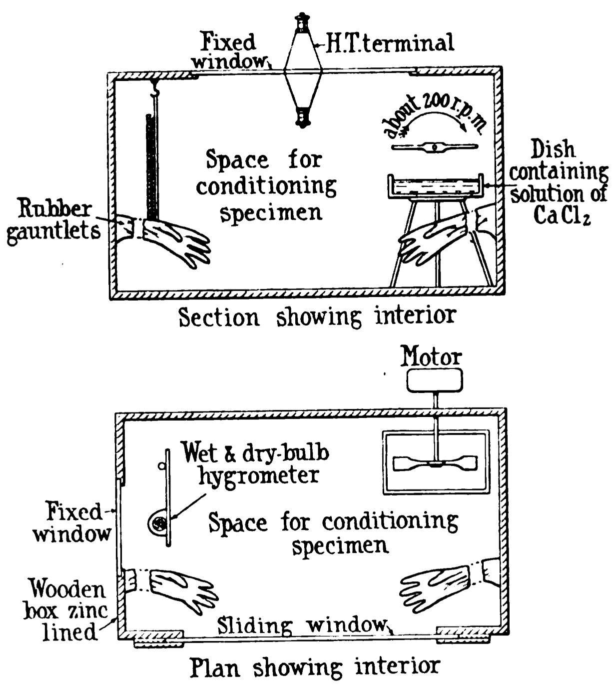


FIG. 19.—Cold conditioning chamber and equipment.

air-tight the fan must be designed as a stirrer only; any difference in pressure between the air in the chamber and the air in the laboratory results in leakage which renders the attainment of a high humidity very difficult.

(ii) *Normal Condition.*

For normal condition a humidity of 75 % obtained by the use of $CaCl_2$ of specific gravity 1·22 at 15° C. is specified. In order that the required humidity may be obtained in all parts of the chamber, especially when the chamber is loaded with specimens, it is essential that the air should be kept continuously circulating over the solution and between and around the specimens. The method shown in Fig. 19 has been found satisfactory.

(*c*) *Measurement of Humidity in Cold Chambers.*

The wet and dry bulb hygrometer is an unreliable instrument if used in still air, but by ensuring that the velocity of the air past the bulb is of the order of 3 metres per second it can be converted into an instrument of satisfactory precision. In the chamber shown in Fig. 19 a window is provided in one side through which the thermometers can be read. This arrangement has been found very convenient.

If for any reason an air velocity past the bulbs of at least 3 metres per second cannot be ensured a dew point hygrometer should be used. The surface on which the deposit occurs should be of well-burnished silver, and the usual aspiration method through ether, alcohol, or water can be used for producing the necessary lowering of temperature.

When temperature differences are small it is important that the fluid be in actual contact with the silver surface if accurate results are required. The temperature gradient through the glass, if a silver thimble is fitted on to a test tube in the usual manner, may be of importance, and the temperature of the fluid will be appreciably lower than that of the silver surface, giving too low a value of the estimated humidity.

(*d*) *Method for Obtaining the Specified Temperatures in Hot Chambers.*

Electrically heated ovens should always be employed. With a view to obtaining as uniform a temperature as possible, the heating elements should be distributed over the whole of the bottom of the oven and the temperature regulated by means of an external resistance. To obtain a wider variation of temperature series parallel connections can be employed, provided all the units are left in circuit. If the specimens and internal fittings are suitably arranged, the convection currents, set up by the heating elements, will be sufficient to keep the temperature and humidity in different parts of the chamber as uniform as is necessary.

(*e*) *Test Chambers.*

With many dielectrics considerable change of moisture content may take place in a very short space of time as the result of change of humidity or of temperature of the surrounding air. The effects produced by the conditioning may therefore be altered if change of moisture content is permitted during the time elapsing from the end of the conditioning period to the determination of the electric strength. When the latter is determined under oil there is less risk of change of moisture content than in the case of tests made in air. When tests are made in air and when it is likely that change of moisture content may occur, the electrical tests should always be made either in the conditioning chamber or, as is usually found more convenient, in an enclosed chamber specially designed for conducting the electrical tests. The use of rubber gauntlets fastened in the sides of the chamber, as indicated in Fig. 19, permits the investigator to change the connections and manipulate the samples without opening the chamber. The glass window at the top ensures good illumination of the interior, by either daylight or artificial light.

APPENDIX VII.

The Determination of the Electrical Characteristics of Insulating Materials at High Frequencies.

H.F. Test No. 1. *The Determination of the Power Factor and Permittivity of Electrical Insulating Materials at Radio Frequencies.*

(*a*) *General.*

The method of test described is put forward in tentative form in response to requests received for information on H.F. tests. The method described is based on the tentative method suggested by the American Society for Testing Materials in its Serial Designation D 150-23 T.

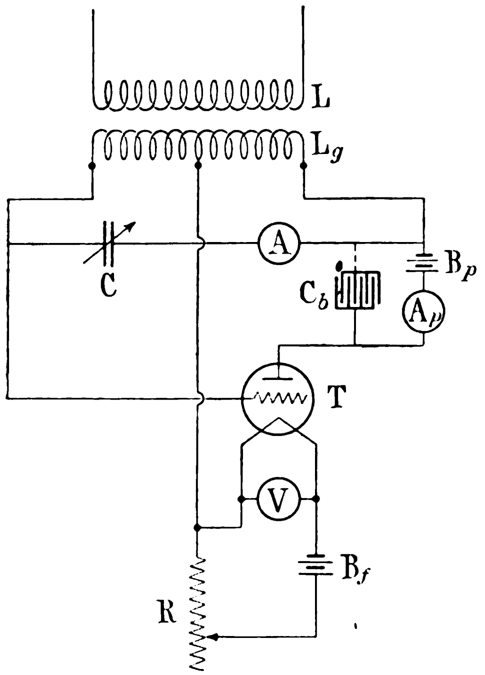


Fig. 20.—Generating circuit specified by the A.S.T.M.

This method of test as developed by the E.R.A. is intended to apply to all solid electrical insulating materials.

The behaviour of material under test at radio frequencies is fundamentally different from that at low frequencies.

In this test the power factor of the dielectric is determined at a measured frequency by determining the effective resistance (or equivalent series resistance) and capacity of a condenser made up with the material as the dielectric. The permittivity is calculated from the measured capacity of such a condenser, and the thickness and area of the dielectric.

The dielectric power loss is proportional to the product of the permittivity and the power factor.

(*b*) *Generating Circuit.*

The circuit in which the radio frequency waves are generated is called the generating circuit. The source of radio frequency voltage shall be an electron tube oscillator the frequency of which can be varied over the range desired and which can be coupled loosely to the measuring circuit. It shall furnish sufficient power so that the presence of the measuring circuit will not reduce its output. The output of the oscillator must be very constant, as any variation in voltage will cause a much larger variation in the final results, because of the differential method used. For this reason it is desirable to have the plate current supplied by a storage battery or other source of very constant power.

The generating circuit must be capable of supplying power at any wave length between 240 metres (1 250 kilocycles per second) and 3 500 metres (86 kilocycles per second).

An arrangement of the generating circuit suggested

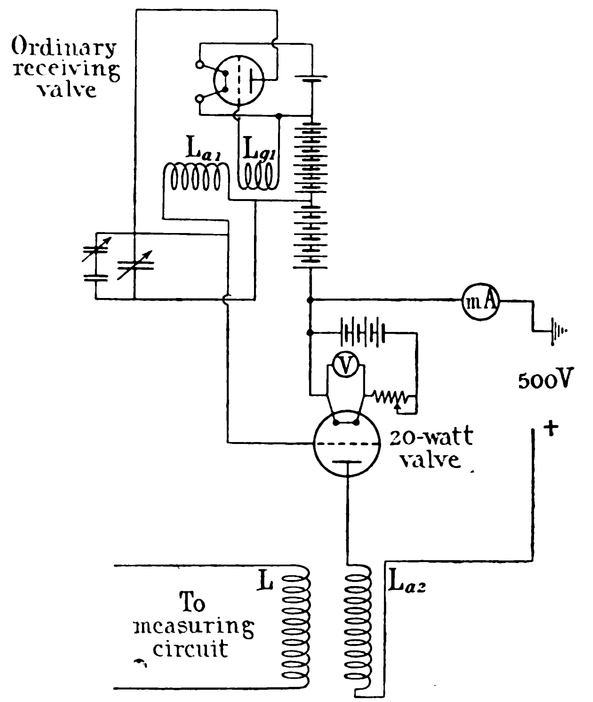


Fig. 21.—Generating circuit used by the E.R.A.

by the A.S.T.M. is shown in Fig. 20, to which the following particulars apply:—

The inductance coil L_g is any one of a series of detachable tubular single layer coils. For the tests outlined it is probable that not more than five will be required. The smaller coil may be made by winding 13 turns of wire on a $3\frac{1}{2}$-inch tube with 6 turns on either side of the middle clip. The larger coil may be made by winding 112 turns of wire on a $6\frac{3}{4}$-inch tube, 32 turns on either side of the middle clip and 24 turns outside of both outside clips. The other three coils may be made to cover the gap between these two extremes.

The variable air condenser C may be of any suitable commercial shielded type having a maximum capacity of about 0·003 microfarads (3 000 micro-microfarads). The ammeter A is of the hot-wire type having a range of 0 to 1 ampere. The by-pass condenser C_b may be

any type of fixed condenser capable of withstanding 500 volts (direct current).

The plate battery B_p may be a 100 to 300 volt accumulator having an ampere capacity of about 0·2 ampere at an 8 hour discharge rate. The ammeter A_p may be any type of direct-current instrument having a range of 0 to 50 milliamperes. The three-electrode electron

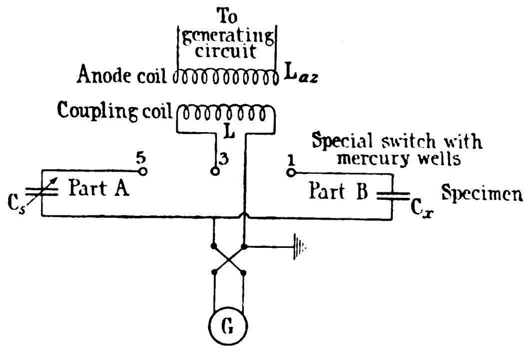


FIG. 22.—Measuring circuit used by the E.R.A.

tube T may be any of the so-called power tubes rated at 5 watts or over.

An alternative arrangement of the generating circuit is shown in Fig. 21. During tests made by the E.R.A. it was found that by using two valves as indicated in Fig. 21 the frequency was much less dependent upon the load taken than it was when a single valve was used.

To cover the required frequency range when employing the circuit shown in Fig. 21 three sets of coils made as indicated below have been found suitable.

For each of the sets coils L_{a1} and L_{g1} were wound

(c) *Measuring Circuit.*

The circuit in which the specimen is placed for test is called the measuring circuit (Fig. 22).

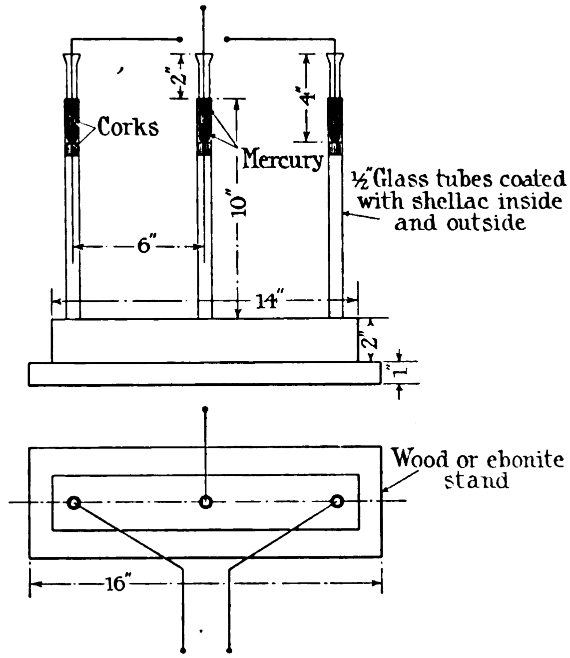


FIG. 23.—Special switch used by the E.R.A.

This circuit is composed of :—

A condenser employing the test specimen as the dielectric and two metallic surfaces as the conducting plates.

	Set No. 1 for wave lengths from 230 to 670 metres		Set No. 2 for wave lengths from 580 to 1 790 metres		Set No. 3 for wave lengths from 1 380 to 4 480 metres	
	Coil marked L_{a1} in Fig. 21	Coil marked L_{g1} in Fig. 21	Coil marked L_{a1} in Fig. 21	Coil marked L_{g1} in Fig. 21	Coil marked L_{a1} in Fig. 21	Coil marked L_{g1} in Fig. 21
Mean diameter (cm)	10·7	10·7	10·7	10·7	10·7	10·7
Length (cm)	2·54	1·15	4·65	1·85	8·6	3·7
Number of turns	26	32	82	52	242	104
Diameter of wire (inches)	0·020	0·0124	0·020	0·0124	0·0124	0·0124
Turns per cm	10·3	28	18	28·2	28·2	28·2
Approximate inductance (microhenrys) ..	100	200	800	460	5 000	1 420

on the same tube, each coil being wound in a single layer, leaving about ⅛ inch between the two coils.

The above mentioned coils are employed in the circuit of the first valve shown in Fig. 21. For the anode coil L_{a2} of the second valve a coil made as follows has been found suitable for the complete range of wave lengths covered by the above :—

Mean diameter = 15·7 cm
Length = 4 cm
Number of turns = 73
Diameter of wire = 0·020 inch
Turns per cm = 18·2
Approximate inductance = 1 100 microhenrys

A standard condenser of a suitable design having negligible power factor.

One or more suitable inductance coils with tappings.

A thermo-element of the vacuum type having a resistance of about 8 ohms when the material under test has only moderately good properties and a lower resistance (say less than 5 ohms) when the material under test has good properties at high frequencies.

A special double-throw switch equipped with mercury wells (Fig. 23).

A set of resistance links having direct-current

resistance values ranging from negligible to about 100 ohms (Fig. 24).

A sensitive low-resistance wall galvanometer of the deflecting mirror type or other suitable type of indicating instrument.

The arrangement of the measuring circuit used by the E.R.A. is shown in Fig. 22. This circuit has been found more convenient than the one suggested by the A.S.T.M.

The standard variable air condenser C_s should have a maximum capacity of about 0·001 microfarad (1 000 micro-microfarads). The special switch with mercury wells is shown in Fig. 23, and one of the non-inductive resistance in Fig. 24. The non-inductive resistance is made as shown in Fig. 24. Several of these resistances are required, but in all cases the distance between the spurs should be the same, because the resistances must fit into the mercury wells in the switch (Fig. 23). Each of these units has a different value of resistance made so by varying either the length or the diameter of the resistance wire or both.

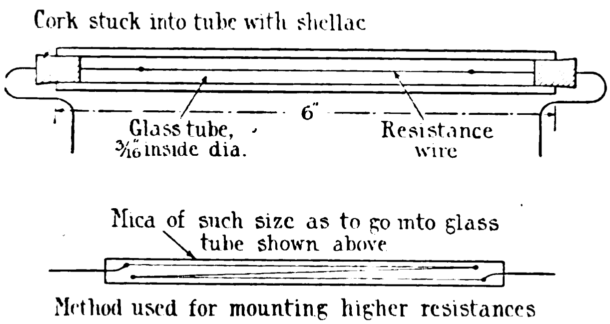


Fig. 24.—Special non-inductive resistance.

The condenser C_x is made either by floating the test specimen on mercury and pouring mercury on the upper surface until it is filled to a confining barrier or by the use of one of the other methods detailed in Clause (*f*). The mercury bath on which the specimen rests is contained in a glass dish which rests on a piece of insulating material which in turn is supported by a levelling device.

The coil L, Fig. 22, must be designed to have a comparatively low resistance so that the coil resistance will not be a large proportion of the combined equivalent resistance of the circuit made up of coil L and the specimen condenser C_x. To cover the frequencies (wave lengths) named, the following coils have been found suitable :—

For wave lengths from about 1 000 *to* 4 000 *metres.*

One single-layer coil wound as indicated below and having seven equidistant tappings has been found convenient.

Mean diameter = 15·7 cm
Length = 20·8 cm
Number of turns = 376
Diameter of wire = 0·020 inch
Turns per cm = 18·2

Approximate inductance of complete coil = 11 500 microhenrys.

For wave-lengths below 1 000 *metres.*

Two single-layer coils wound as indicated below and on the same tube arranged with a space of about 2 cms between them have been found suitable.

Mean diameter = 10·7 cm
Diameter of wire = 0·020 inch

Coil 1 consisted of 45 turns and had an inductance of approximately 300 microhenrys.

Coil 2 consisted of 15 turns and had an inductance of approximately 50 microhenrys.

For further regulation of the inductance a coil 4 cm in diameter and wound with 45 turns in 3 layers of 0·018 inch diameter wire giving an inductance of approximately 100 microhenrys was suspended inside the above coils. The small coil can be conveniently used with the other coils either as a variometer or as a loading coil.

The thermo-element T is of the crossed-wire vacuum type. The resistance of the thermo-element should be from 3 to 8 ohms.

The galvanometer G is a sensitive wall galvanometer of the deflecting mirror type. One having a resistance of about 30 ohms and a deflection at a distance of 1 metre of about 80 mm per microampere has been found suitable.

It has been found very important to arrange the circuits quite symmetrically with respect to the coupling coil and the anode coil. Unequal coupling between the coils and points A and B of the measuring circuit, Fig. 22, causes appreciable errors.

(*d*) *Conditioning of Specimens previous to Test.*

The power factor and permittivity of each sample shall be tested after being conditioned as follows :—

(i) Normal conditions as defined in Appendix I.
(ii) After immersion in distilled water for 48 hours at about 20° C., followed by exposure to normal conditions for 24 hours.
(iii) After being freely exposed for 24 hours to a dry atmosphere at 90° C.*

(*e*) *Condition of Specimen during Test.*

Tests shall be made as indicated below :—

(i) With specimens previously exposed to " normal " condition and whilst exposed to an atmosphere of normal condition.
(ii) With specimens previously immersed in water as (ii) in Clause (*d*) above and whilst exposed to an atmosphere of normal condition.
(iii) With specimens previously exposed to 90° C. and whilst at 90° C.*

(*f*) *Preparation of Test Condenser.*

The following methods are suggested for preparing the condenser required for measuring the power factor and the permittivity of the material :—

(i) *For Rigid Materials in the Form of a Sheet.*

Either circular or rectangular test specimens may be used, and the specimen shall be of such dimensions

* If the grade temperature of the material is less than 90° C., the conditioning and the tests shall be made at the grade temperature.

that the capacity of the condenser shall not be less than 200 micro-microfarads (200 $\mu\mu$F). For a thickness of specimen of $\frac{1}{8}$ to $\frac{1}{4}$ inch a specimen about 12 $\times$ 10 inches is usually satisfactory.

The test condenser is made by floating the specimen on mercury and by placing mercury in an enclosure on the top of the specimen. When tests are to be made at low temperatures the enclosure for the mercury may be made by casting a rim of wax on the top surface of the specimen and situated about 1 cm from its edges. For tests at high temperatures the mercury may be enclosed by means of an amalgamated metal rim placed on the top surface of the specimen and of such dimensions as to leave a clear space of 2 cm from the outer edge of the rim to the edge of the specimen.

(ii) *For Materials in the Form of Tubes.*

The dimensions of the tube shall be such as to enable a condenser of not less than 200 $\mu\mu$F being made. One end of the tube shall be plugged with a tight-fitting rubber cork and the condenser made by putting mercury into the tube and placing the tube in a tall glass vessel containing mercury to the required level.

(iii) *For Flexible Materials.*

The use of tinfoil as electrodes for flexible materials has been found unsatisfactory. Suitably constructed mercury electrodes have been found to give consistent results. Fig. 25 shows an apparatus which has been found satisfactory for flexible materials. The apparatus consists of two cast-iron blocks A in which are cut shallow circular recesses to hold the mercury. The rims of these recesses are made only 1 mm wide and accurately flat, so that when the arrangement is tightened up they form a good fit. Four bolts are fixed into lugs on one of the cast-iron clamps, and passing through holes in corresponding lugs on the other enable the clamp to be tightened by nuts. The insulation between the two points consists of amber washers, through which the bolts pass. The mercury is poured in from below through glass tubes which are cemented into holes bored in the casting, with a cement made from red lead and bakelite. For thin materials a cast-iron clamp having a mercury space about 3 inches diameter has been found satisfactory.

(*g*) *Method of Test.*

The test condenser prepared as stated in (*d*) above shall be arranged in the measuring circuit as stated in (*c*) and the radio-frequency generator arranged as in (*b*).

The measuring circuit is divided into two parts at the special switch; by connecting wells 1 and 3 the circuit is completed through the specimen, and by connecting wells 3 and 5 the standard air condenser is placed in circuit.

The three wells being unconnected the generating circuit is switched on, the galvanometer zero adjusted, a link of negligible resistance is inserted between wells 1 and 3, and the resonant frequency obtained by adjustment of the main condenser of the generating circuit Fig. 21, previously calibrated against a wave-meter. The magnitude of the galvanometer deflection is brought to nearly full scale by bringing the anode coil of the generating circuit nearer to the coupling coil of the measuring circuit. To make sure that an alteration in the position of the anode coil does not affect the zero reading of the galvanometer the link may be removed from 1 to 3 and the zero checked. The final adjustment of frequency for resonance is in the case of the circuit shown in Fig. 21 effected by means of the vernier condenser, and the galvanometer deflection then read. The link is next removed from wells 1 and 3, and replaced by a resistance of such a value that the galvanometer deflection is reduced to about half. A

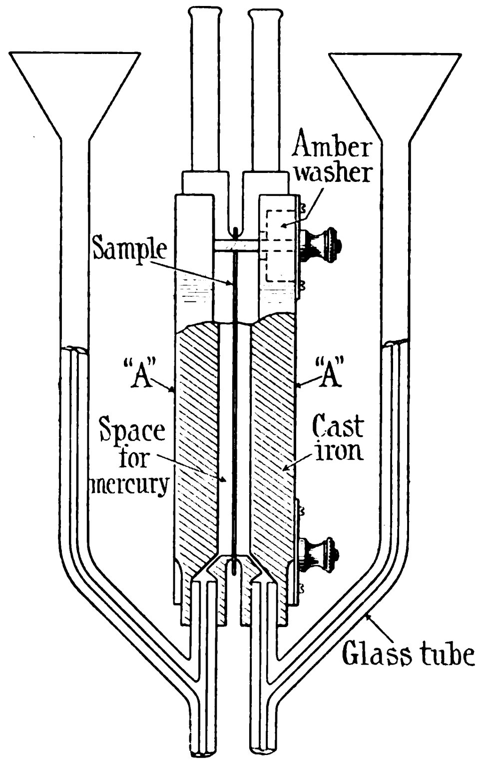


FIG. 25.—Apparatus used by the E.R.A. for the measurement of the power factor and permittivity of flexible materials.

slight adjustment of the vernier condenser may be necessary for exact resonance, and, this being done, the deflection is again read, the process is repeated in succession with three or more resistances, of values such that the deflections lie between a third and two-thirds of that which is produced without any added resistance. Then the link is again replaced and the maximum deflection read. This should be the same, to within 0·5 per cent, as that obtained at first.

The procedure detailed above is now repeated with the other part of the circuit, i.e. using wells 3 and 5, the only difference being that the main condenser of the generating circuit is left untouched, resonance being obtained by adjustment of the air condenser of the measuring circuit. The resistance of this part of

the circuit being smaller than that of part B, Fig. 22, looser coupling and smaller resistances are required.

(*h*) *Calculation of "Equivalent Resistance" of Specimen.*

In this calculation it is assumed that the condenser with the test specimen as dielectric is equivalent to an air condenser of the same capacity and zero power factor in series with a non-inductive resistance called the " equivalent " or " effective " resistance.

The equivalent resistance of the specimen is calculated as follows :—

Referring to Fig. 22,

Let R_x = the resistance of the specimen C_x.
R_s = the resistance of the standard air condenser C_s.
R_c = the resistance of the remainder of the measuring circuit including the coupling coil L.

Then the resistance of Part B = $R_x + R_c$, and that of Part A = $R_s + R_c$.

As the standard condenser may be considered to have negligible resistance, the resistance of the specimen is that of part B minus that of part A.

The resistance of parts A and B is calculated from the experimental values of galvanometer deflection and added resistance as follows :—

Let R_o = the resistance of the circuit with no other resistance inserted.
R_i = the resistance inserted.
D_o = the galvanometer deflection with no other resistance inserted.
D_i = the galvanometer deflection with resistance inserted.

Then

$$Ro = \frac{R_i}{\sqrt{\frac{D_o}{D_i}} - 1}$$

From the values obtained by inserting the three or four resistances, make three or four calculations of the resistance of parts A and B, take the average value for each part of the circuit, and the difference of these values gives the equivalent resistance of the specimen at the frequency used for the test.

(*j*) *Calculation of Power Factor.*

Let R_x = the equivalent resistance of the specimen in ohms.
C_x = the specimen capacity in micro-micro-farads.
λ = wave-length in metres.

Then power factor $= 0\cdot188 \dfrac{R_x \,.\, C_x}{\lambda}$ per cent (approx.).

The equivalent resistance of the specimen is calculated by the method detailed in (*h*) above, the specimen capacity is obtained from the reading of the standard air condenser, and the wave-length from a wave-meter.

(*k*) *Calculation of Permittivity of Specimen in the form of a Sheet.*

Let C_x = capacity of the specimen in micro-micro-farads.
T = average thickness in cm.
S = area of dielectric subjected to electric stress, and expressed in square centimetres.

Then permittivity $= \dfrac{C_x \,.\, T}{0\cdot0885 \,.\, S}$

(*l*) *Dielectric Loss.*

As the energy loss in a dielectric is dependent on both the power factor and also on the permittivity the best comparison of electrical insulating materials for use at high frequencies is obtained by considering the product of the power factor and permittivity.

(*m*) *Acknowledgments.*

As stated in Clause (*a*), the above method of test is based on the tentative method suggested by the A.S.T.M. in its publication Serial Designation D 150–23 T.

Certain features of the above method are based on uncompleted researches by Mr. D. W. Dye, B.Sc., and Mr. L. Hartshorn, B.Sc., both of the National Physical Laboratory. Certain other features are based on uncompleted researches at City and Guilds Engineering College by Prof. C. L. Fortescue, O.B.E., M.A., and Mr. J. E. P. L. Vigoureux, B.Sc.

H.F. Test No. 2. Comparison of the Effect on Electrical Insulating Materials of High Voltages at Radio Frequencies.

(*a*) *General.*

Methods of test for comparing the effect on electrical insulating materials of high voltages at radio frequencies are under investigation by the E.R.A. Pending the results of these experimental investigations attention is drawn to the tentative method suggested by the A.S.T.M. in its publication Serial Designation D 175–23 T. With but minor modifications, the above mentioned A.S.T.M. publication is reproduced below :—

(*b*) *Effects of Applying a High Voltage at Radio Frequencies to Insulating Materials.*

This method of test is intended to determine the electric failure and flash-over voltages of electrical insulating materials at radio frequencies.

The failure under radio frequency stress may take the form of charring, buckling, cracking, blistering, softening or chemical decomposition. Failure through the material is not abrupt, and it therefore requires a certain amount of judgment on the part of the operator to decide just what constitutes failure in any particular case.

When a sheet of insulating material is tested between two metal electrodes passing through it, the heat generated increases with the thickness of the material, while the radiating surface remains nearly constant. Consequently, as the thickness of the sample is increased, the voltage at which failure occurs will decrease. As

sufficient data are not available to allow results to be translated from one thickness to another, it is necessary that all comparative tests be made on samples of the same thickness. Hence, in the standard method given below, a definite thickness of sample is specified. This method, of course, is applicable to other thicknesses of material, but when so used the results should be compared only with similar tests made on like thicknesses of material.

In the flash-over test, heating of the material due to the high-frequency current is to be avoided, and it, therefore, is not so important that the samples being compared be of the same thickness. However, as a little heating is unavoidable, it is also desirable in this test to compare samples of the same thickness whenever possible.

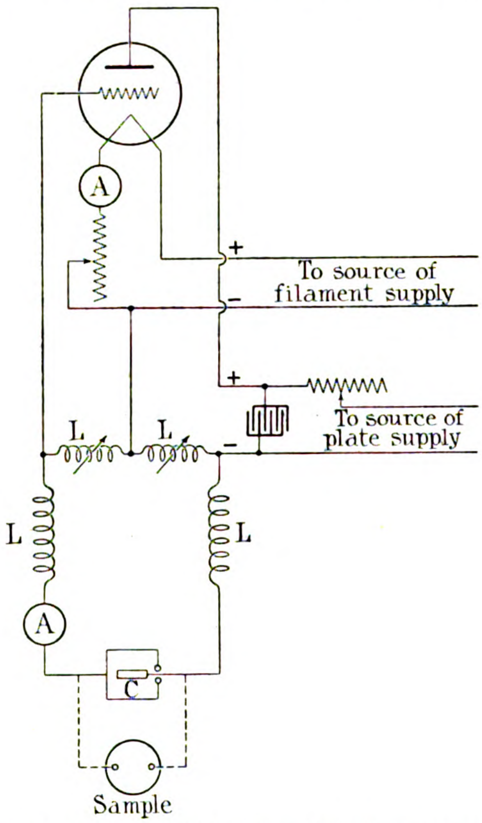


FIG. 26.—Circuit for high-voltage high-frequency tests.

(c) High-voltage High-Frequency Generator.

Any type of generator having an output of 500 watts or more and generating continuous waves of 100 and 1 000 kilocycles per second, respectively, and at voltages up to 5 000 or 10 000 volts, depending upon the class of materials tested, is satisfactory. If desired, a circuit similar to that shown in Fig. 26 may be used.

(d) Measurement of Voltage.

The voltage may be measured by means of the current through a shielded radio frequency ammeter in series with a small shielded air condenser of known capacity across the test terminals or by means of an electrostatic voltmeter designed to withstand radio frequency potentials. Suitable scales shall be provided so that reasonable accuracy will be obtained when measuring any testing voltages up to the maximum desired.

If the ammeter method is used :—

$$E \text{ (in volts)} = \frac{16I \times 10^7}{fC} *$$

where I = current in amperes,
f = frequency in kilocycles per second,
C = capacity of air condenser in micro-micro-farads.

(e) Electrodes.

The electrodes shall be of brass and shall be clean and polished.

For the dielectric failure test through the specimen the electrodes shall have the dimensions shown in Fig. 27.

For the flash-over voltage test across the surface of the material, the electrodes shall have the dimensions shown in Fig. 28.

(f) Test Specimens.

The specimens shall be representative of the material to be tested, care being taken to select material free from abnormal defects.

For the dielectric failure test, the specimens shall be 6·35 mm (0·25 in.) in thickness and may be of any convenient size or shape provided that the centre electrode (see Fig. 29) is at least 57·5 mm (2·264 in.) from the outside edge at all points. Other thicknesses may be used, but the results therefrom should be used strictly for comparative purposes as explained under Section (*b*). If any samples are milled to reduce the thickness, care should be taken not to tear, chip or otherwise change the character of the material. Four holes 12·7 mm (0·5 in.) in diameter, shall be provided in each specimen, one in the centre and three equally spaced in a circle of 25·4 mm (1·000 in.) radius as shown in Fig. 29.

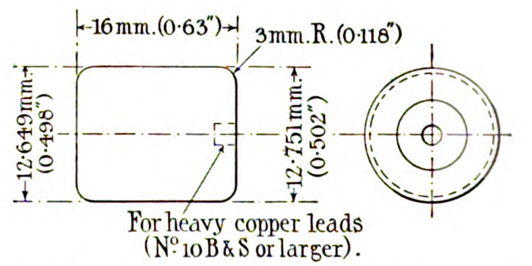


FIG. 27.—Electrodes for testing through the material.

For the flash-over test, the specimens may be any convenient size, the holes being drilled on 38·1 mm (1·5 in.) centres as shown in Fig. 28.

(g) Conditioning of Specimens previous to Test.

The effect of high voltage at high frequency shall be

* In the formula the value 16 is an approximation, 15·92 being the exact value.

determined after specimens prepared in accordance with Fig. 28 have been conditioned as follows :—

(i) Normal condition as defined in Appendix I.*
(ii) After immersion in distilled water for 48 hours at about 20° C., followed by exposure to normal condition for 24 hours.

instant when the prescribed voltage is reached, and the time required to reach this voltage not exceeding ½ minute. Whenever samples thicker than that specified are used, this testing period should be changed to three minutes.

Tests shall be made between the centre hole and each of the other three holes of each specimen, the specimens

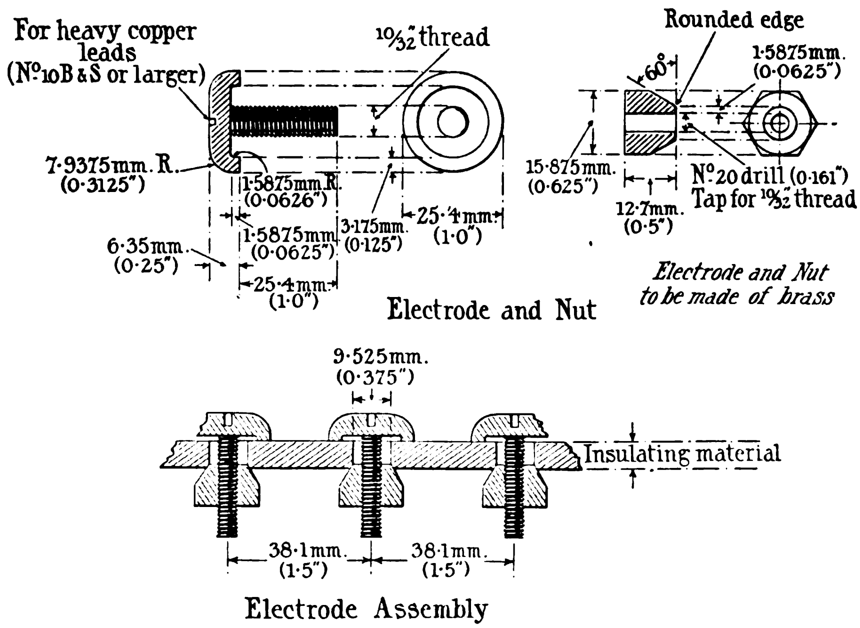


FIG. 28.—Electrodes for testing across the surface of material.

(h) Condition of Specimen during Test.

During test the specimens shall be exposed to an atmosphere of normal condition as defined in Appendix I.*

(j) Method of Test for Failure through the Material.

One electrode (Fig. 27) shall be inserted in the centre hole in a specimen and a similar electrode in one of the other three holes. The electrodes must be a tight fit, otherwise corona may form at comparatively low voltage and destroy the material.

The electrodes shall then be connected to the test terminals of the radio-frequency generator. One side of the generator shall be earthed, and this terminal shall be connected to the centre electrode of the specimen. The reason for this is that the failure generally occurs around the high potential terminal and this will allow the two subsequent tests to be made between the centre and the other two holes, the centre not being destroyed.

For materials which ordinarily fail below 3 000 volts the voltage shall be raised in steps of 500 volts. For materials which ordinarily fail above 3 000 volts, the voltage shall be raised in steps of 1 000 volts. Wherever possible, the initial voltage chosen shall be such that at least three voltage steps will be required to cause failure of the material.

The voltage at each step shall be impressed for two minutes, the testing period being counted from the

* Appendix I of Ref. L/S2.

being allowed to cool to room temperature after each test.

The average of these three voltages shall be considered as the electric strength of the specimen under the conditions of the tests.

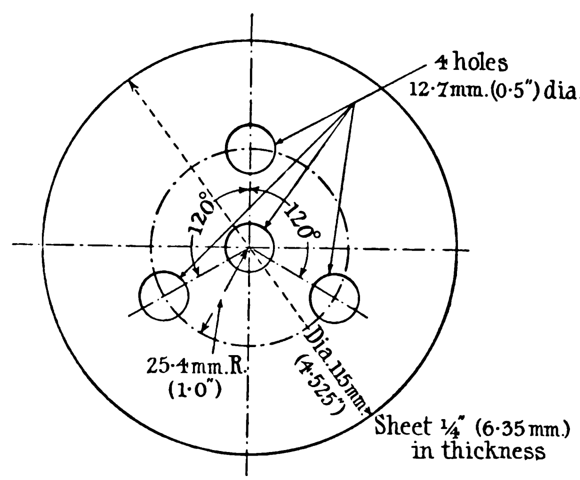


FIG. 29.—Specimen for high-voltage high-frequency.

Specimens shall be tested at 100 kilocycles per second (3 000 metres) and also at 1 000 kilocycles per second (300 metres).

(*k*) *Method of Test for Failure across the Surface of the Material.*

The flash-over tests shall be made under the same conditions and at the same frequencies as specified in (*j*) above.

The electrodes shall be clamped into position as shown in Fig. 28.

The voltage shall be raised at * the rate of about 1 000 volts per second until flash-over occurs. The power shall be removed immediately upon flash-over and the test shall be repeated (without moving the electrodes) until the insulation value has been practically destroyed.

* The voltage may be increased either by varying the grid and plate inductances or capacities or by varying the D.C. plate voltage.

The initial voltage chosen shall be as little below the flash-over voltage as practicable so that the flash-over will occur as soon as possible without appreciable heating of the material.

The voltage which exists across the specimen when flash-over takes place cannot be determined with the specimen in place since the voltage would not remain constant until a steady deflection of the measuring instrument was reached and the sample would heat up. Therefore, as soon as discharge occurs the plate voltage shall be thrown off, all other controls remaining constant, and the test leads removed. The plate voltage then shall be reapplied and the voltage measuring instrument reading taken when a steady deflection is reached.

Tests shall be made in at least three places on each side of each specimen.

INSTITUTION NOTES.

Associate Membership Examination.

The next Examination will be held on the 15th, 16th and 17th April, 1926. Candidates must be either Students or Graduates of the Institution or have lodged with the Secretary a duly completed form "E" for election as Associate Member. Entry forms for the Examination, which must be completed and returned by the 1st February, may be had on application to the Secretary.

Associate Membership Examination Results.

OCTOBER 1925, SUPPLEMENTARY LIST.*

Passed.

Anderson, J. P. (South Africa).
Burke, R. T. (India).
de Beer, C. L. (South Africa).
Eales, A. B. (South Africa).
Freeman, C. E. (South Africa).
Gillespie, A. (South Africa).
Lester, A. E. (South Africa).
Loveday, G. K. (South Africa).
Nash, W. A. (South Africa).
Stanton, W. A. (South Africa).
Wood, C. F. (South Africa).
Wright, A. M. (U.S.A.).

Passed Part I only.

Collins, H. (South Africa).

* See page 92.

Passed Part II only.

Ambalavanar, P. (Ceylon).
Chapman, R. F. (South Africa).
Dawes, E. A. (South Africa).
Gray, T. A. (South Africa).
Rhenius, S. T. (India).

Further results relating to other candidates who sat for the Examination will be published later.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 November–25 December, 1925 :—

	£	s.	d.
Anonymous	1	1	0
Devis, E. R. (London)		6	0
Johnson, A. (Birmingham)		4	0
Johnstone, A. B. (East Murton, Co. Durham)		10	0
Merz, C. H. (London)	2	2	0*
Mortimer, S. (Penang)		8	6
Pepper, W. O. (Bradford)	1	0	0
Shaw, C. M. (London)		2	6*
Simpson, S. (Leeds)		5	0
Tyler, A. S. (Whitstable)		5	0
Uttley, E. A. (London)		10	0

* Annual Subscriptions.

THE ENGINEER: HIS DUE AND HIS DUTY IN LIFE.

By THOMAS CARTER, Member.

(*Paper first received* 13*th May, and in final form* 9*th June,* 1925; *read before* THE INSTITUTION 19*th November, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 16*th November, before the* NORTH-EASTERN CENTRE 23*rd November, before the* NORTH MIDLAND CENTRE 24*th November, and before the* NORTH-WESTERN CENTRE 1*st December,* 1925.)

SUMMARY.

(1) THE RIGHTS AND THE DUTIES OF LIFE.

In these days, when many standards of the past are disappearing, when new thoughts are being conceived and new views are struggling for recognition, and when more than ever the safety of the future depends on the well-directed efforts of men of wide vision and clear understanding, it is not too much to say that unless each of us is contriving somehow to increase the common good, he were much better dead. It was a very profound thinker who said: " When ye shall have done all the things that are commanded you, say, We are unprofitable servants; we have done that which it was our duty to do." Has it not been the exceeding of mere duty that has hoisted the lamp of knowledge a little higher and has furnished it with a brighter light, so that the confines of our ignorance are not so narrow as they were, and the darkness still to be searched is less terrifying than once it seemed?

We are born into a family, into a nation, into the world; we inherit from all the past; we are played upon by things around us, and we react on them in our turn; each one of us has his own qualities, his own defects, his own potential contribution to the service of his fellows. In theory, at least, the nation desires each of its members to have the fullest opportunity for self-expression, so that the aggregate excellence may be increased. But unless the members work in harmony, there will be mere confusion; unless the many feet of a centipede all decide to carry the body in the same direction, the poor animal may find it difficult to avoid an early death. There are, then, two sides to a man's life, together making it complete: the one, his right to live; the other, his duty to the community. As to the first, the lethal chamber at birth would be a kinder fate than the life that some people unfortunately grow up to. If we let a child live, we must in decency see that no great unclimbable rocks are left lying in his path. His right is to expect to be prepared in his youth for a job that he can do in his working days with enough comfort to leave his spirit unquenched if he grows to be old. Political thought seems to be groping after some means of achieving this, but the free meals, the free education, the doles, and all the other things that are handed out, are not even the beginning of the kind of care that should be lavished on us. In these there is death to the nation in the end rather than the intense common life that we ought to grow into, and until we learn how to use our human resources adequately we shall lose much that may be had for the taking. On the other hand, the more we give every man a chance to reach his best, the more must he recognize that this good comes to him from the community, and the more must he strive, while following his own bent, to avoid every activity that will put a brake on the wheels of progress. This, then, is a proper life: a constant giving and receiving, a perpetual interchange of services, ideas, and commodities, with an unfailing consideration of our neighbour's good as well as of our own, and a constant recollection that those who forget their common obligations, and merely demand their own due without caring what happens to others, are the slayers of the nation's soul. There is no right without its corresponding duty.

(2) THE RISE OF MODERN ENGINEERING.

The world has never been wanting in engineers. Almost before the dawn of history, Zillah, the wife of Lamech, " bare Tubal-Cain, the forger of every cutting instrument of brass and iron"; and his kind have always played a leading part in human development. The famous buildings of the past witness to the greatness of the engineers who created them; and the works of early races and of the Middle Ages sometimes put our own to shame.

The Oxford English Dictionary tells an interesting story in its articles on words referring to our profession. " Engine" is related to the Latin " ingenium," and to our " ingenious." It first meant " native talent" or " mother wit." It was also used in the senses of " natural disposition," " skill in contriving," and " ingenuity," and, later, in the transferred sense of " a product of ingenuity" or " a device," and sometimes " a snare" or " a wile," like the kindred word " gin." Then it came to mean, more narrowly, " a mechanical contrivance," especially in the restricted sense of " a large mechanical instrument of warfare"; and finally, after denoting generally " a machine, with parts working together to produce a given physical effect," such as, for instance, a watch, it acquired its modern significance in words like " steam-engine" and " heat-engine." The word " engineer," that is " one who is concerned with engines," has varied similarly in meaning. It first denoted " a contriver or designer or inventor," sometimes in the special sense of " a layer of snares," as in the phrase " That great engineer, Satan." Later it was applied to constructors of military works, and

then to designers and constructors of works of public utility, named civil engineers for distinction from military engineers, who had previously carried out public works also.

The modern engineering profession has grown up within the last two or three hundred years as a consequence of the new interest in science and scientific investigation that arose in the sixteenth century. Sir Hugh Myddleton, who died in 1631 and who conceived the New River water scheme for London, has been called "the first English engineer"; and names of great men, like Newcomen, Brindley, Smeaton, Watt, Telford, Rennie, the Brunels, and the Stephensons, meet us in the succeeding period. Associations of engineers began to arise. "Before or about 1760," (I quote from the preface to Smeaton's Reports) "a new era in all the arts and sciences . . . commenced in this country. . . . Manufactures were extended on a new plan . . . by men of deep knowledge and persevering industry engaged in them. It was perceived that it would be better for establishments to be set down in new situations . . . than to be plagued with the miserable little politics of corporate towns, and the wages of their extravagant workmen." A demand arose for internal navigation as a means of communication, and "this general situation . . . gave rise to a new profession and order of men, called Civil Engineers." Some of these engineers used to meet in the Houses of Parliament and in the Courts of Justice, without knowing much of each other, and someone proposed to Smeaton that "it would be well if some sort of occasional meeting, in a friendly way, was to be held, where they might shake hands together, and be personally known to one another; that thus the sharp edges of their minds might be rubbed off, as it were, by a closer communication of ideas, no ways naturally hostile; might promote the true end of the public business upon which they should happen to meet in the course of their employment; without jostling each other with rudeness, too common in the unworthy part of the advocates of the law, whose interest it might be to push them on perhaps too far in discussing points in contest. . . . In March, 1771, a small meeting was first established, on Friday evenings, after the labours of the day were over, at the Queen's Head Tavern, Holborn. . . . Conversation, argument, and a social communication of ideas and knowledge, in the particular walks of each member, were at the same time the amusement and the business of the meetings." In May, 1792, a disagreement caused the dissolution of the Society, but it was afterwards revived "in a better and more respectable form." The members dined together and passed the evening "in that species of conversation which provokes the communication of knowledge more readily and rapidly than it can be obtained from private study or books alone. The first meeting of this new institution, The Society of Civil Engineers, was held on the 15th of April, 1793." There were three classes of membership: Ordinary Members were real engineers, employed as such; men of science and gentlemen of rank, who might, for talents and knowledge, have been engineers, together with persons employed in kindred public service, formed one group of Honorary Members, and a second consisted of various artists, whose professions and employments were useful to civil engineering. The meetings were held at the Crown and Anchor, in the Strand, every other Friday during the session of Parliament, and an early list of members shows 12 real engineers, 10 of the first kind of Honorary Members, and 7 of the second, namely, a geographer, two instrument makers, a millwright, an engine maker, a printer, and a land surveyor. So much for this predecessor of all our present-day Institutions.

The Institution of Civil Engineers, established in 1818, and chartered in 1828, nobly defined the profession of a civil engineer, that is, of any engineer not a military engineer, as "the art of directing the great sources of power in nature for the use and convenience of man"; The Institution of Mechanical Engineers began in 1847, and The Institution of Naval Architects in 1860; and the Society that grew into The Institution of Electrical Engineers was founded in 1871, as a mark of the progress of the new science that began to find its modern application when Faraday discovered the existence of electromagnetic induction in 1831. The engineer of to-day has the whole range of natural forces to deal with; and in no department of his profession is the variety so great as amongst electrical engineers. Our Institution has for its members some who roam at will in the tiny empty space between the nucleus and the electrons of an atom, not only seeing with some special vision the wonderful processes of that region, but actually taking matter to pieces and remaking it differently; some who, at the opposite end of the scale, construct machines so large that one of them will keep the wheels turning for thousands of workers; some who take these machines and build them into power stations; some who run these power stations, and test them complete as a single machine used to be tested, always endeavouring to make more and more use of the energy of their fuel; consultants who work out schemes for the application of electric power; public advisers who regulate and co-ordinate the electrical resources of the country; those who install plant and wire buildings; those who teach others; those who control communication with and without wires; those who made that kind of communication possible; and many others. All these are engineers, every one in his own sphere trying to direct some great source of power in nature for the use and convenience of man.

(3) The Finding of Engineers.

Having obtained a conception of what constitutes a proper life, and having reminded ourselves of what an engineer is, let us think how the life of an engineer may have its fullest usefulness. We have not long begun to realize how much a problem like this concerns us as a nation. Some children are born to be engineers, and some to be anything but engineers: our part is to separate the engineers from the others. We make far too little attempt to ascertain whether those who decide to be engineers have done so merely because their parents think it right, or because they have somehow drifted aimlessly into it; or whether, on

the other hand, they are real engineers. We also let many escape into other occupations who should be compelled to come into engineering. The finding of engineers to train is far more important than the finding of methods of training them. First catch your hare, then cook him, says the old saw; but be sure he is a hare, and do not merely label your snare "For Hares," and then take whatever you find in it, if you are really fond of hare soup. Strictness at the beginning may reduce the number of those who become engineers; but that is what is needed. The proper selection of potential engineers and the rejection of all others would so increase the efficiency of the profession that there would be no lack of directing ability. To keep its place in the world, a nation must more and more cherish and utilize every one of its members to the fullest of his possibilities; somehow (it is a matter for the patient thought of the very best men amongst us to discover exactly how) we must cease to be haphazard. Faith, and the vision of the unseen goal, will be needed; but they are not wanting, and they will suffice.

In pursuit of our aim, we must discover the inmost nature of children at an early age; and it may be hoped that teachers will more and more try to do this as part of their work. Tests of intelligence and vocational tests are being made tentatively in many places, both of children still at school and of those passing out into employment; and although much time will be required before their data can be properly interpreted, some very suggestive information has already been collected. By checking attainment against prediction, thus keeping abreast of each child's development, it will eventually be possible for the head of a school to give definite advice regarding the career of at least some of his scholars. There will always be many who are without marked bias, who will go through life doing mostly as they are told, and who will perhaps do as well in one thing as in another. It is the head-and-shoulders-higher-than-their-fellows people whom we want specially to discover; but only by watching all will these be found. So we shall avoid, on the one hand, the keeping down of a leader amongst the led, and, on the other, the letting through to the leader's place of one who is bound to fail.

Dr. Johnston, of Highgate School, has very kindly sent me some notes of what is being done there in this connection. The records of all boys, even those of average capacity, are systematically studied as they go through the school, so that they may be guided into appropriate callings. Dr. Johnston writes: "I cannot pretend that we have achieved very much, because the problem bristles with difficulties. As a nation, we are quite unorganized; there are no records kept in public offices of the state of supply and demand in the various professions, and all boys have to face the welter of extreme competition without any knowledge of the facts. The question of a career is therefore in most cases determined almost entirely by accident rather than by a careful survey of the fitness of persons for particular walks in life. There are two ways in which help can be given: first, and in practice more important and helpful, though it is on the negative side, we are able to inform parents with great confidence what form of activity the boy should not attempt, and in this way we can correct the prejudices that may have been formed about the boy's future work." After instancing one who rightly became a journalist instead of the engineer his parents wanted him to be, and another who is now a brilliant scientist and a possible future Fellow of the Royal Society, having been rescued from the prospect of a quite different kind of career, Dr. Johnston says: "With respect to your own profession, I have always advised parents to let no boy become an engineer unless he combines in his capacity two particular forms of talent: (*a*) real aptitude in dealing with scientific apparatus and adapting means to ends, and a real feeling for the purpose of machinery in general; and (*b*) distinct capacity in the practical applications of mathematics and the use of mathematical formulae for utilitarian purposes. If he has higher mathematical knowledge and could deal with the abstractions of theory, so much the better, and he might become a better and greater designing engineer. . . .

"Secondly, on the positive side I have found it possible to do a certain amount, but not very much. It is easier to make positive recommendations in the case of boys with scientific bent than those with a bent for language and literature. . . . I have dealt with boys who showed no liking whatever for language work, but were incomparably handy and fertile when they came to deal with instruments in a physical laboratory." Dr. Johnston mentions two such people, who might have been regarded as hopeless according to the older-fashioned view, but are now on the high road to become experts in wireless engineering and broadcasting; he then states that of the many positive suggestions that are given, all valuable in some way, 20 or 30 per cent yield important results; and he concludes by saying: "The engineering boy is one of the most difficult to determine, because nowadays a very large proportion of boys can mend a bicycle pump or find out very rapidly why a motor car will not start or run properly; but I want the boy who can inspect a structure and tell instinctively what parts are in a state of tension or pressure, and what must be done to ensure stability; I want the type of boy who, pouring a fluid into a vertical vessel, will almost visualize the descent of the centre of gravity at first and its subsequent rise as he goes on, who could plot and graph the process and get results even if he could not complete the question mathematically. If this kind of boy takes to mathematics and can learn to use the principles of the differential and integral calculus, he is, from my point of view, the right kind to make an engineer. But he must have both forms of talent: one without the other makes an intelligent foreman or an unpractical theorist."

The value of this comparatively new work of investigating intelligence and capacity is clearly enormous, and as it extends, and more experience is gained, its increasingly definite results will allow more and more accurate estimates to be made. Further, a boy's personality will develop finely under treatment like this; he will discover that he is an individual, not merely a drop in an ocean, but a separate being, capable of impressing himself upon others; he will climb so high in thought that great things and small things will

appear to him truly related in his ever-widening view; if he is more than usually favoured, he may even, looking higher, see the "dawn of more than mortal day strike on the Mount of Vision."

The careful guiding of boys to the discovery of the dominant tendencies in them, and of the things to be rooted out before their best powers can have full scope, is exactly what is wanted to prepare them for the still more specialized training of the next stage of their development.

(4) The Training of Engineers.

I will not do more than mention the several varieties of engineering education; their details have frequently been described far better than I could do it. Some take a college course, followed by a short apprenticeship in workshops; some go straight from college to administrative work; some serve a long works' apprenticeship and get what theoretical training they can in their spare time; some, following sandwich systems, alternate in longer or shorter periods between study and practice. Each method has its advocates and its advantages, and suits the circumstances of some students more completely than others; but in all of them, let it be repeated, the one great essential is to see that the people put through the process are real engineers. If this were secured, more value would come to be placed on a record of achievement than on the result of an examination; there would be far less weeding out to do than there is now. There would be small chance that a purely academic man would be put to research work in matters where intimate practical knowledge is required; or that a merely practical man could cause calculations and minutely thought-out instructions and even carefully prepared drawings to be regarded as very nearly superfluous; and possibly the perennial question of the engineer-salesman would be found to have solved itself. Perhaps, too, although we seem to have reached the end of discovery and initiation in some directions, and to have settled down largely to a working out of details, we should find amongst the new engineers some who would hit upon really new principles, or ways of combining things so novel that, as in the transverter, for example, they practically embody a new principle. To one who said that a man could achieve anything if he were made of the right stuff, Steinmetz is reported to have replied: "The scientific fact is that people are made out of the right stuff, but our problem is to find a way to release their creative energies."

A very useful summary of the obviously necessary scope of an academic engineering training was given a few years ago in the *Journal* of The American Institute of Electrical Engineers; I cannot do better than use its words:

A. It should offer directly:

- (1) Instruction in engineering knowledge, both
  - (*a*) fundamentals, and
  - (*b*) specific applications.
- (2) Instruction in non-engineering subjects, such as English, Economics, Law.
- (3) Instruction and training in hygienics.

B. It should also make adequate provision for:

- (4) Inculcation of habits of clear thinking, concentration, persistence, observation, decision, imagination.
- (5) Infusion of principles of fairness, unselfishness, tolerance, refinement, courtesy.
- (6) Formation of friendships.

To live the life we have been thinking of, with its reciprocal aspects of individual growth and service to the nation, such men are required as were turned out by Job Huss, the schoolmaster in H. G. Wells's "Undying Fire": "I have had dull boys and intractable boys, but nearly all have gone into the world gentlemen, broad-minded, good-mannered, understanding and unselfish, masters of self, servants of man, because the whole scheme of their education has been to release them from base and narrow things."

There may be many opinions about what and how an apprentice must learn as he goes through the works; but one thing is sure: he will be dependent for his instruction almost entirely on others employed there, and he must commend himself to them in his personal bearing and his general friendliness if he is to get all that he can out of his intercourse with them. Besides being an open book for the student of human nature, a factory brings the learner into contact with people who in ways not described in manuals or in college courses have inherited the skill and the traditions of the past, and hold in themselves the power to teach him the knack of doing things. One of the awful losses occasioned by the war was the destruction of the personal knowledge and aptitude of so many tens of thousands who lie quietly at rest in ground that they have made their own for ever, and by reason of whose departure to the place from which no word of these things comes back we are immeasurably poorer. All the more, then, must a young man be thankful now if he can find an older man with knowledge, willing to take his hand and lead him on. It is so difficult for anyone to see ahead the exact niche into which he will eventually fit that the only safe rule is to acquire and store up either in his memory or in some other accessible place all the information presented to him, however varied it may be, and however apparently out of the line of his immediate work. Then, if in the days to come he has to direct the work of other men, he will know by unfailing instinct in what terms he should issue his orders, because he knows so well the way in which they will be carried out. A wise old book, now out of print, said: "Politeness is as indispensable to a learner in the works as to a gentleman in society. The character of the courtesy may be modified to suit the circumstances and the person, but still it is courtesy. . . . Without the art of questioning, but slow progress will be made in learning. . . . There is not a more generous or kindly feeling in the world than that with which a skilled mechanic will share his knowledge with those who have gained his esteem."

Thus are worthy leaders made; and here, as always, the development of personality, the acquirement of the art of standing firmly alone and yet all the time making contact with those around, is still the thing that counts

almost more than anything else. For a man possessing it will be in living touch with life, and will add knowledge to knowledge, and strength to strength, until his last day; he will more and more easily distinguish the temporal from the eternal; he will move confidently amongst great thoughts and great affairs. "The aim of education," says the COPEC report on that subject, "is the full and harmonious development of the resources of the human spirit, the making of the perfect man or woman. Such a one will possess a single wide interest; a consistency of feeling, thought, and conduct; a perfectly integrated personality rightly related to the society from which it is inseparable."

(5) Principles and Problems.

There are fundamental things that all of us must bear in mind at every stage of our career, if we are to avoid pitfalls. We are bound in our work by conditions that require first of all our promises and afterwards our adequate performance of them; how needful it is, then, that those who direct the work shall have clear thoughts, flexible ideas, and so wide an understanding of the possibilities of any undertaking that out of the varied views that may be held they will select the one best calculated to ensure success. The very facility with which we may pick up a smattering of a subject nowadays, and the ease with which a thin veneer of showy knowledge is spread over great slabs of essential ignorance, may lead us back to the conditions of the dark ages, if we are not careful. When men had to puzzle things out for themselves, many of them could survey and carry out a whole job, but this is rather the day of the specialist, who is limited to his own sphere; and although the change was perhaps inevitable, because of the expansion of the range of our subjects, in many respects the old way was, for once, better than the new. If we are to apply our knowledge to the best advantage in our practice, we must keep it as varied as we can, consistently with thoroughness; and, in addition to knowledge, we must try to acquire and preserve the wisdom that will show us how to use it. The man who with wide-open eyes sees most will constantly find opportunities thrust on him for seeing more. What we call luck is often nothing else than a readiness for the coming chance, and an immediate grasping of it when it arrives. Alas for us if we let it go by! The moment's hesitation that loses it might as well be an eternity. I recall how once at a travelling menagerie, when I was a very small boy, I was offered a ride on an elephant's back, and for some reason of childish fear refused it. But at night I wept bitterly, repenting in vain of my negligence, for even an elephant will not wait for ever, and the unreturning caravan had passed on. So a proverb has arisen in my family: "Remember, you may wish you had ridden on the elephant."

The reports we must make and the records we must keep will be of more value as we ourselves acquire a greater facility in the accurate use of words. Our power to communicate with each other at all is a perpetual wonder. We write marks on paper; and when we pass them from one to another, they somehow convey ideas and summon thoughts. We open our mouths and make sounds; and they, like the writing, mean something to those who happen to be near. It is as great an insult to a hearer or to a correspondent to be slovenly about our words as it would be if we gave him a picture that we had first slashed into ribbons. So we must assure ourselves that we know what we want to say—no easy matter in itself—and then we may attempt its expression in words. It is terribly difficult to write sentences and paragraphs with only a single meaning, even if we try; how impossible it is if we have never troubled to realize the difficulty! Our aim should be to keep clear of extremes on either hand. The wife of one of the dictionary makers, a convivial fellow, returned home one night unexpectedly to find him carousing with his companions. "Well, sir, I am surprised," said she. "No, madam," was the reply. "You are astonished: I am surprised." We need not cultivate so pedantic an exactitude as this; but we must equally avoid falling into such mental confusion as caused the schoolboy to declare that, according to Euclid, things that are trebles of the same thing are trebles of one another. A study of the great writers and poets will lead us to some sense of the fitness of words, and will keep us clear of the dreary baldness of expression to which we are so prone. We get habits in writing our letters that tie us down to a painfully small vocabulary; and a written application for a position is often the one thing that prevents a man from being interviewed. I do not suggest that we should draft our bye-laws so that they can be made into an anthem, or that we should write our specifications so that they would more naturally be sung than read; but if we realize the essential music of things like the praise of love by Paul the Apostle to his friends at Corinth, the everlasting beauty of Keats's "Ode to a Nightingale," or the perfect fitting of expression to meaning in Hamlet's last words: "The rest is silence," we shall make bye-laws and draw up specifications and write letters far better than if we had never thought of these lovely things. Ben Jonson says: "The best writers in their beginnings imposed upon themselves care and industry; they did nothing rashly; they obtained first to write well, and then custom made it easy and a habit. By little and little their matter showed itself to them more plentifully; their words answered, their compositions followed; and all, as in a well-ordered family, presented itself in the place. So that the sum of all is, ready writing makes not good writing, but good writing brings on ready writing."

Our incomplete understanding of the mechanism of the universe, our inevitable lack of knowledge of all the conditions and circumstances that will affect a piece of work, and often the mere shortness of time itself, compel us to realize that, in so great a complexity as we have to deal with, our judgments must sometimes be partial, and only our experience can guide us into the probably right path. We help ourselves by using formulæ; but unless these are truly based on first principles, or unless we understand their limitations and keep in mind the physical facts behind them, they are the most dangerous of our tools. Formulæ are of two distinct kinds. The first are a mere shorthand notation, like multiplication tables, or like an algebraical

expression that states some invariable relation in a convenient form. These are safe so long as we use them appropriately and make no mistake in our calculations based on them. Even if an error does arise, it can usually be discovered by the simple means of checking the end against the beginning. Formulæ of the second kind are expressions of generalized conclusions drawn from experiments. Their value depends both on the competence of the investigator and on the completeness of his investigation, and the limits within which they may be safely used must be very carefully stated and observed. Interpolation is then reasonably safe; extrapolation is occasionally fatal, and always dangerous. Natural laws, the great generalizations of master minds, are formulæ of this order, and all through the ages they have had to be revised and restated and often rejected in the light of new knowledge. The old statement serves for a time, and then some quick eye sees a discrepancy between it and something that looks like a fact. Either the seeming fact is no fact, or the law is untrue; and it is from a refusal to smooth out a kink in a curve merely because it has been said that there should be no kink, or from a confident scepticism that will not force a new idea to square itself with an accepted view merely because it is accepted, that many a great advance has come.

A resolute determination to avoid preconceived conclusions, to allow just enough play to the imagination, to face facts at every stage, and not, as it were, to refuse to look in the last corner of a room for a lost coin, in case it should not be there either, will bring us to the point at which we can say: "Thus and thus ought we to do"; we shall be wise if we do it then once and for all, and pass on to the next task with the satisfaction that comes of achievement. To engineers, above all other men, faith is essential; the faith that removes mountains, not by sitting still and wishing them gone, which will never accomplish anything, but by setting out with picks and shovels, and hacking and digging and carting away, in the sure belief that at length, however long it lasts, the end of the job will come.

Difficult and complicated as are our technical problems, those of us who deal directly with men, either in controlling their work, or in negotiating affairs with them, are faced with still harder human problems. Many subjects in this region are so controversial that they cannot be touched on here; but we may consider a few things that will fit us to think clearly about them. It is not easy to secure a correct statement of some of the problems, especially if they are debated by partisans; and the inmost facts themselves are often not accessible. In discussions, words are used vaguely, or even with no recognizable meaning at all; they may become mere catchwords, thrown about as missiles rather than exchanged as currency of thought; and here, if anywhere, we must think for ourselves. Our equipment must therefore be adequate, and we shall do well to dig down into all sources of reliable information on such questions as unemployment; industrial relations between owners of concerns and those who manage them or earn wages in them; the effect on men of the gradual change from much manual labour to much minding of machines; the consequences from the national point of view of the conditions involved in mass-production; the problem of leisure, and whether in efforts to secure more of it those who are striving are forgetting that leisure implies occupation either in amusement or in recreation, and that the demand thus created for things that amuse and recreate will not go unsatisfied. Dr. Jacks says, in a recent article in *The Hibbert Journal*, "Of course we may imagine our community spending its long leisure in a state of mental or bodily torpor. . . . But as education increases the activity of men's minds and the vigour of their bodies, it is hardly to be expected that they will adopt this way out of the difficulty. Nor would it prove altogether effective if they did, as we were forcibly reminded by the wife of a Yorkshire miner with whom we were discussing these things. After remarking that 'short hours for the men mean long hours for the women' (a fact which not many sociologists have noted), she described at some length the leisure occupations of her husband, who at the moment was asleep upstairs, and then wound up as follows: 'When he's nowt else to do he lies abed; and that wears out the sheets, which I has to mend'—the economics of leisure in a nutshell."

To think out the details of the processes by which the ordinary things of life are made possible—for example, how it is that I can buy a pair of boots—is undoubtedly one of the best methods of realizing the dependence of every one thing upon every other thing; and a recognition of the kindred fact, that none of us liveth unto himself, will allow a man to meet his fellows with the success that comes from feeling his way tactfully amongst them, instead of ramming his views down their throats. "Although there exist," someone has written, "many thousand subjects for elegant conversation, there are persons who cannot meet a cripple without talking about feet." That is the way to kindle resentment against us in the hearts of others, some day to burst out and bring much pain that could have been avoided had sufficient care been taken. We simply must recognize that there are many points of view, and that it is at least worth while to see whether some of the others are not as tenable and as satisfying as our own. Robert Louis Stevenson has a fable about intolerance. "Be ashamed of yourself," said the frog. "When I was a tadpole I had no tail." "Just what I thought," said the tadpole. "You never were a tadpole." This is particularly apt as a parable of the feeling that often exists between the old and the young.

We must acquaint ourselves with the principles of economics sufficiently to avoid confusion when we think or read or talk of them. Some of the subjects we should try to be clear about are:—The fixing of prices for profitable output, and the relation between prices and turnover; ways of increasing production, without which not much advance can be looked for; the basis of national finance, with a recollection that taxes are not imposed for fun, and that national activities have to be paid for all the time; whether it would have been better to scrap all our war surplus as part of the wreckage of the war, and thus to keep some men, now unemployed, working at their own jobs instead of being dependent on national charity and in danger of becoming unem-

ployable; the meaning of a gold standard, and why it does not necessarily imply an internal gold currency; the usefulness of paying a man a large salary to do nothing but go round looking at things in his works, in the country, and abroad, and drawing conclusions from what he sees; the meaning of fluctuations in foreign exchanges as they concern the economic position of countries internationally; whether there are ascertainable reasons for the apparently more or less regular periods of good and bad trade, and whether any means can be discovered for smoothing out the variations so as to make prosperity more continuous; the essential importance of never doing a thing ourselves if we can find someone else to do it well for us; the whole problem of trade union conditions, how far they have been useful and how far not; the study of industrial fatigue, and how to use the results of the study; the impossibility of both eating our cake and having it; the sound sense, as the Chinese proverb says, of selling one loaf, when we have two, and buying a lily instead.

A few simple rules will keep us right in our meetings with others. Remember that although conventions may seem very stupid, they are usually based on common sense, and should not be too rashly broken through. Remember that while a continuance of endeavour in the face of difficulties is sometimes hard, its continuance when success comes is often harder and more noble. Remember that, as Walter de la Mare reminds us somewhere, the bears under the bed are all the more terrifying because they are not real bears at all. Remember the inestimable worth of humour, and cultivate every real spark of it. Remember that there is a time to keep silence, and a time to speak. "Refrain not speech, when it tendeth to safety; and hide not thy wisdom for the sake of fair-seeming. . . . If thou hast understanding, answer thy neighbour; and if not, let thy hand be upon thy mouth." Remember the value of friendship: a friend, they say, is one who knows all about us, and likes us in spite of it. Remember that small achievements often have frightful striving behind them. The farmer asked the boy: "What are you hanging round there for? Trying to pinch them apples?" "No!" said the boy. "I'm trying 'ard not to." Remember the pitifulness of much in human life; how fleeting it all is; how little we can foresee. Remember that each present moment is but a thin partition between the irrevocable past and the future that is always inevitably emerging from it, as a flower, fair or loathsome, springs from a planted seed.

(6) Engineers and Public Life.

One of the most remarkable things about engineering is that there is scarcely a region of the world's activity into which the engineer's direct influence does not extend. If we think through the whole of history, we shall find that his work has somehow entered into everything; but its effect on society has been most marked since the comparatively recent time when men began to devise aids to their own strength and capacity so powerful that they ushered in a new era. The whole fabric of commerce is kept in being to-day by the efforts of engineers; if they were to cease, it would perish as completely as if the world itself had stopped. Engineers have gone on inventing, often enough not realizing that the results of their work might be used for merely commercial ends, and in such ways that they could not conduce to the convenience of man. It is largely because of what engineers have done that towns have grown up, with their grey skies and crowded dwellings, and that our mode of existence, from being quite simple, has become oppressively complex and hurried. The world has been rendered almost immeasurably small by modern methods of transport and communication, and we have become so used to its smallness that we scarcely ever pause to consider whether it is good for us. The contrivances of engineers having made so much of this possible and even inevitable, although perhaps no moral responsibility attaches to their part in it, must not they now, when they see the monster that has been created, design some new contrivance that will so mollify and tame it that the world may once again be safe? To change the metaphor: The mechanism rattles and rumbles as it works; cannot those who made it discover a lubricant for it?

On the whole, engineers have not taken much part hitherto in public life. It is true that many of them are by nature not fitted for it, though that is not to say that all who are in it now are pre-eminently suitable. Some engineers, however, in addition to their technical accomplishments and their ingrained habits of reflection and investigation and logical deduction, have so clear a view of what is wrong in affairs generally, and of what may have to be done to put it right, that they ought certainly to be in positions of wide authority, dealing with public problems not merely as engineers, but as men of the world with special qualifications because they are engineers. To take only one example: Some of them, by their contact with all sides and all parties, may actually have had even more opportunities of arriving at an understanding of industrial problems than some of the people officially concerned with them; and their help would be invaluable in the discussion of such questions.

Efforts after improvement are being made in many directions: a League of Nations Committee on Intellectual Co-operation is trying to bring together for common aims teachers and students all over the world; the whole industrial situation is being analysed by competent people in discussions and writings; a Government Commission of inquiry into the conditions and prospects of British industry and commerce was set up in 1924; the co-ordination of technical education and its relation to other branches of education and to industry are being considered; those who lead in industry are feeling more and more their responsibility as the channels through which the opportunity must come for those under them to live adequately in return for services rendered through them to the community; and the attitude of all recent Governments towards these matters has revealed their view that they are the concern of the nation and not of individuals alone. But the way out of the turmoil will only be found by patient thought and long consideration and conference; and the public-minded engineer is peculiarly well suited for this. Parliament cannot do much to devise remedies; its main province is to register in its Acts the state of public

opinion at a given moment, and thus to create conditions favourable to progress along desired lines; and it is for those who are faced by any problem to work out a solution for it, and then, convinced that they have found it, to ask Parliament to sanction it. If some engineers were also members of Parliament and of other great deliberative bodies, many problems would be passed into practice with increased effectiveness, and the whole outlook of public life might be redirected for the better. Thus would full usefulness be reached in service to the nation; engineering would become a still finer thing than it is; and the life of an engineer would be more desirable because his work would be more highly appreciated.

(7) Conclusion.

I have tried to take, and put into words, a few of the thoughts that have come to me about the common things of our common life. The mind of each of us colours every view differently as it looks at it from its own standpoint; but there may be agreement on fundamental things, and our examination of some of them now may bring us a more vivid realization of them. I would plead specially for consideration of the problem of the finding of real engineers to be trained, and of the suggestion that engineers have it in them to smooth out much that is now tangled and to throw light on many obscure things. I think that we must try to consider more than we have done, in the literal sense of being alone with the stars; in the great open spaces we shall find enlightenment and rest and peace. We shall discover there that the man who wrote the 23rd Psalm is worth more to us than all the noisy and futile people who built the city and the tower of Babel. We shall realize that although we tear aside the veil that hides the last secret of the material universe, we can never take away the enduring reality that makes things pure and noble and beautiful. We shall find that however hard it is to see even the closest things clearly, there are some glad certainties that can never grow dim. We shall learn in quietness to refresh our soul.

I heard a broadcast voice utter three great words: "Justice, Freedom, Fellowship"; and perhaps these sum up the worthiest aims of all existence, and so of every single life. The individual dies and disappears, but our great profession continues, perfecting itself through change succeeding change. I see the mighty loom of the universe at work, and the strands of its warp are old things, long known, like birth and death and love and hate; others as old, but discovered only yesterday, like protons and electrons and the transmutation of elements; and still others whose nature cannot as yet be clearly discerned. I myself and all my fellows are the weft, passing to and fro among the alternating threads to make the pattern of the piece that stretches between the two infinities, putting into it every bit of us, our faults, our excellence, our frequent negligence, our strong endeavour. And I perceive that without each one of us, however little or however much we contribute to the finished web, the unending variety of the design cannot be fully worked out.

Discussion before The Institution, 19 November, 1925.

Mr. J. Swinburne: The author has rightly treated his subject very widely; and I will follow his example, and begin with the general or school education of a boy. Education should, I suggest, (*a*) enable a man to earn his living, (*b*) make him a good citizen, (*c*) teach him how to be healthy, and (*d*) enable him to enjoy his leisure. The early education of a boy cannot well be vocational; but at present it is nothing more than iniquitous waste of the best years of a man's life. Beyond reading and writing, and sometimes elementary arithmetic, the young man from the public schools and universities really does not know anything that counts, and cannot earn his living. There was an early civilization in Egypt, and the Egyptian astronomers and engineers did work which was very wonderful for the time. I may mention incidentally that the engineers were priests. When the more barbarous Greeks overcame Egypt they absorbed their knowledge. Later the still more barbarous Romans overcame the Greeks, and absorbed their knowledge. It was then the fashion for Roman highbrows to admire the culture of Greece, probably unaware that it was largely of Egyptian origin. Then when the Roman Empire fell, mediæval Europe was completely controlled by the priests. In order to keep the public ignorant the priests kept Latin to themselves. The Bible, for example, was in Latin, so that laymen should not learn its contents. The clergy were the only people supposed to know anything, and what they knew, especially Latin, was considered to be learning. Even scientific men wrote in Latin. The clergy had complete control of education; and their whole object was to bring people up so as to support the Church. In addition to that, a priest has a type of mind which has immense reverence for the authority of earlier ecclesiastics, and a hatred of any reasoning, or knowledge of facts. The result is that education has developed along narrow clerical lines. The priests kept Europe in the dark or retarded civilization about 1 000 to 1 500 years. They do not now prevent knowledge directly, as their teeth have been drawn; but they have left us a legacy of bonds, if one can use such a mixed metaphor, and we are only just beginning to throw them off during the last two or three centuries. Education, as it is now, consists mainly in training the memory; or exercising it, and letting its exercise train it. There is not even any systematic training of memory. The stuff that the memory is exercised in acquiring is not knowledge. A language is not knowledge—at most it is a means of acquiring knowledge; but had either the Greeks or the Romans any knowledge worth our acquisition? The author mentions Keats. When some highbrows were appreciating Keats, a mere person asked "What is a keat?" The highbrows may really have liked it, or have thought it was correct to admire all the conventional classical allusions with which Keats is

saturated; but it is quite likely that the person knew more than the highbrows. The knowledge of the "educated" man counts only because others have it, and not to have it is a drawback. Its value is not real; it is purely conventional. Ability to epitomize the "Catalogue of the Ships" is of no value whatever, and does not raise an Englishman above a Hottentot. The person who asks what a thebe is but knows that he does not drink down his throat, is to that extent superior to the university man and the Hottentot. There is no hope for boys' education until it is got out of the hands and influence of the clergy. The clergy cannot now control education so as to preserve their pre-eminence by keeping laymen ignorant, but they run it along obsolete and wrong lines. It is difficult now to realize the power of the clergy in the past, as school history books do not mention it. For instance, up to the sixteenth century parsons held many of the most important and lucrative public positions. It is said that in the early part of the fourteenth century very nearly half the soil of the kingdom was in the hands of the clergy. Even now the architecture of the Law Courts is ecclesiastical, the law terms are those of the Church year, and some of the judges change their robes according to the church seasons. But the greatest evil at present is that people admire, and therefore try to cultivate, a type of mind which depends on memory, does not reason or think for itself, is subservient to authority and precedent, and is really stagnant. Engineering is the essence of common sense and the perfection of applied logic. When an engineer is tackling a technical problem he uses his logical brain. When he discusses anything outside his special subject, such as any of the public questions of the day, he does not apply his logical mind at all. He is just as stupid as anyone else, because he uses only his fallow mind, and is just as full of the ignorant prejudices we call opinions as is anyone else. Some years ago there was a public discussion among engineers on "Free Trade and Tariffs." It was clear that the disputants thought the question could be settled without any knowledge or study of economics, by the application of vulgar sense. In designing a new kind of polyphase machine an electrician does not depend on vulgar sense, nor does he make it according to the opinions of some class, or in accordance with the leading articles in his favourite daily paper: he studies electrotechnics and uses his brains. If he has to design a boiler house, he does not say "I advocate phlogiston; down with those who believe in the caloric theory." As engineers use their logical minds in connection with boiler houses, both the phlogiston and caloric notions are dead long ago. Now the dynamic theory of heat is not a century old, but no one questions it. The theory of international trade is a century and a half old, but it is not generally understood, because, being a matter of general and not individual concern, even those who have trained minds do not apply them, but approach the subject with their fallow minds only. A democracy is by its very nature a community of fools governed by the greatest of the fools. But it does not follow that all the fools are fools in every way. Every individual may be sensible enough in his own work, where he uses his trained mind, and quite foolish about all public matters. It may be asked how an engineer who wants to apply his trained mind to matters of general interest such as poverty, war, or narrower questions such as wages, housing, international trade, is to do any good. Is he to go into Parliament? If he talked sense at the election no one would vote for him: and if he could get into Parliament and talked sense he would be of as little use as J. S. Mill was. Is he to improve the world by voting wisely? There is no opportunity. Two candidates are up. Neither has any knowledge of sociology, economics, finance, hygiene or anything else of any value. Both are ambitious for self-advertisement only. To anyone who has thought, both their policies or collections of policies are idiotic, and are merely sops to the prejudices of the ignorant; and the engineer feels that it is a national calamity whichever gets in. Suppose he votes; his vote is negatived by that of some hooligan who believed something one of the candidates said, and accidentally voted for the other because he was too far intoxicated to know which was which; or by the hooligan's wife, who had been got at by the local Womens' Federation For Putting Themselves In Evidence. Now in engineers' society the layman will not air engineering opinions, because he realizes he is in the presence of people who know, and he does not like to make a fool of himself. If the same layman meets a sociologist he will air his opinions on social questions without realizing what an ass he is, because he does not understand that there is anything to know. If the majority of engineers, or even a small percentage, were to apply their active minds to public questions, the average man would eventually realize that he was always making an ass of himself, and in time people would grow to be afraid of expressing ridiculous opinions, and would study public questions out of mere self-respect. If a proportion of the numerous engineers of this country used their trained brains on public questions, it is quite possible they would start a leaven which would, in time, leaven the whole lump. I do not believe they will.

Dr. S. Z. de Ferranti: One conclusion that may be readily drawn from the paper is that however great knowledge is, character is greater still. The author has dealt principally with the professional engineer. The term "engineer" is very broad and, in a sense, somewhat indeterminate. I do not think we can be all quite agreed upon the definition of an engineer. I should like to remind members that outside the engineering profession (and in that term I include the makers of machinery just as much as the writers of specifications) there is an enormous class of engineers, and one which in these present days is growing extremely rapidly. To-day there is a great deal which is mechanical; we all desire to enlist mechanism to lighten our tasks. We use a steam engine or an electric motor, or a combination of them, to do the mechanical work which once was done very largely by manual power. A business man instead of writing innumerable letters employs a shorthand writer and a typewriter to lighten his labour, and so gets through a great deal more work than it was possible for him to do before. Perhaps some day when engineering has developed it may be possible to

dictate into a machine which will simultaneously type a letter, or there may be some better instrument invented for conveying a message and recording it. From time to time various devices are invented and put into practice which lessen labour, but none of them can be fully useful unless they can be dealt with by engineers. Hence it is fortunate that the number of engineers in the world is growing so rapidly. The motor-car, which has been with us many years, has done a good deal to make mechanical engineers of the bulk of the population. When I say " make mechanical engineers " I mean to say giving people mechanical knowledge which enables them to handle machinery carefully and to exercise some care in order to keep it going properly. Wireless telephony, which is a much more recent thing, has made us all into electricians. To-day an amateur handles not only a wireless set, but all the various contrivances he uses, with an extraordinary amount of technical knowledge. In fact, the great advancement which has been made in wireless telegraphy and telephony—the development, really, of the whole thing after the original idea was given to the public—has been brought about by the amateur electrician, another form of engineer. And it is more than ever certain that the great bulk of the population of a country will in the future have to be fairly good engineers; that is, if we wish to live (I speak in the physical sense) with the greatest comfort in respect to the amount of effort we put forward. I should like to touch on another side of the question. The professional engineer has very often to do much more than develop and perfect, and make useful mechanical things. If he has ideas which he thinks he can work out to the point when they will be useful to the community, thus fulfilling one of the author's ideals, he has first to obtain the means of bringing about this result. That entails the use of his persuasive powers upon people to come to his help to enable him to carry out the work of investigation and construction and the putting into practice of his ideas. For this purpose a general knowledge of character becomes of very great importance. Just think of the position of some of the great engineers of the past. Think what George Stephenson had to do to persuade people to build railways. Surely the engineering of men is a more difficult task than the physical engineering of things. When George Stephenson was building the Liverpool and Manchester railway he had to cross Chat Moss—a terrible place to deal with. Many people thought that the railway would never be taken across it, but he was determined to do it, and he did it, but he had to go week after week to his Board and tell them that the embankment, or the way through the Moss, was no nearer completion than it had been a few weeks before. The material that he used kept sinking. It seemed as though the ballast for the line to make up the permanent way was being poured into a bottomless pit; and I am sure that the greatest mental effort and the most wonderful personality must have been brought to bear in so keeping up the courage of those men that they went on and enabled him to bring that engineering work to a success. Take another great man, the French engineer, de Lesseps, who made the Suez Canal. Everybody seemed to combine to discourage him, to tell him of the impossibility of the work, the uselessness of it when it was done and the undesirability of having such a thing at all, but he had that high courage which enabled him to go ahead in the face of difficulty and he persuaded people to give him that support which was necessary to carry out that great work. I have had some little experience in my own way in trying to develop things electrically in the City of London. A great many people said that it was ridiculous to try to bring current from a power station down the river to supply London. They said it would be fatal, and our opponents—I think quite rightly from a business point of view—even went so far as to get an ordinance passed that this high-pressure current was of such a dangerous nature that it ought not to be used in the Royal Palaces and public buildings. They succeeded, and we were handicapped in consequence. That is just an example of the difficulties that we continually experienced. In those days there was no machinery with which we could carry out our ideas. We had to scheme out everything for ourselves, and everything that we did failed, and yet we had to go on devising other means. Then there were the risks which had to be taken. It certainly was, in the then state of electrical engineering, a very dangerous thing to handle 10 000 volts. It was expressly stated in the Board of Trade Regulations that no part of the circuit should be connected to earth. It was essential, with a system which should give the necessary safety for such a supply, that the conductors should be earthed at the generating station and at the substation, and for earth provision to be made in other places; and one had deliberately to break the law and do what one was prohibited from doing, and take the personal risk of that in case anything went wrong and people were killed or any great injury resulted. The engineer experiences all these difficulties. He not only has the mechanical and electrical problems to deal with, but he also has to engineer people if he wishes the country to have the benefit of what he thinks right. I do not complain; I think it is a good thing. I think that opposition does a great deal of good, just as a critical discussion is very valuable before any new idea is adopted.

Mr. C. E. G. Hinshelwood: As Dr. Ferranti has just said, the ideals set forth by the author are indeed very high, and it seems to me that, although it is easy for the higher class of engineer to follow those ideals and to absorb them, it would be a great asset if some of these ideals could be absorbed by the working class. If that were so I am sure that a great proportion of the present industrial troubles could be solved. In all trades union disputes the worker thinks mostly of himself and pays but little consideration to the community, whereas if he followed the author's suggestions he would be able to help not only the nation but industry as well. From the point of view of the education of the engineer, the author has detailed various schemes which can be followed, and has said that it is desirable for engineers to be more carefully selected. At present many hundreds of engineers are produced every year, and out of these only a very small proportion can ever hope to gain success in engineering. If the selection were more carefully made, the right men would get to

the top, and the rest would not have ambitions instilled in them which they can never hope to attain. The average engineer would then have a better chance of getting a good appointment, whilst those who are not really engineers at heart could turn their attention to other professions.

Mr. W. Day: The ideas embodied in this paper are characterized by exalted aspirations and generous enthusiasm. Nevertheless, in my judgment the author's treatment of his great theme is somewhat disappointing and inadequate. It is disappointing for this reason: A great deal, if not most, of what is contained in the paper is equally applicable to all professions and to all honourable callings and has no special significance for the engineer as an engineer. Practically the whole of Section (1), and the greater part of Sections (4), (5) and (7), with the alteration of a few words or the elimination or addition of a sentence, might be taken to apply to all callings. I consider the treatment to be somewhat inadequate because the author does not sufficiently emphasize and stress the unique and permanent contribution of engineers to the common weal, to which I hope to refer later. In Section (3) the author suggests that he believes in the possibility of a social organism arranged with geometrical precision and it appears that he favours some form of academic selectivity for the engineering profession, ultimately involving a limit to the number of engineers. If that were theoretically desirable—although of course in practice it is absolutely impossible—for the engineering profession, then it is equally desirable for all professions and indeed all callings. Assuming, however, that such limiting conditions are possible, I should like to ask the author what he would do with the residue of the population. Carried to its logical conclusion, his proposal amounts to State regulation of birth control, which may be scientific but is certainly not humane. Then again, with regard to the academic selection for the entrance to any profession, we know that insight into the potentialities of personality is extremely rare. Distinguished men have spoken here to-night of men who have overcome great obstacles, but will anybody have the temerity to suggest that those great qualities were discovered by their teachers? They were developed in after life by dint of overcoming obstacles. The proper solution to this question seems to be the open door to all duly accredited persons. This method gives the nation the greatest possible area from which to select. Again, many of the statements contained in the paper are, I submit, too nebulous to be of value. Take the reference to the lethal chamber. What does it amount to? It is of no practical value whatever, even if we could determine, in any section of the community, the potentially unfit. The author refers to unclimbable rocks, and he suggests that free meals, free education and doles are death-dealing proposals. But he does not suggest what should be put in their place at the present time. No statesman has ever considered the free gift of these things as desirable in itself. This has been done to meet special emergencies. Statesmen cannot amuse themselves by constructing hypothetical Utopias. I think that the contributions which engineers have made to the common weal consists in this—that they have continually extended the powers and elevated the happiness of mankind, and that more than any other single profession, not excluding the medical, and certainly not excluding the theological. The progressive application of increasing physical knowledge has constituted, and does constitute, an exceedingly fruitful contribution to the construction, maintenance and improvement of the fabric under which men dwell. That, in my opinion, constitutes the peculiar, the unique, and the permanent contribution of engineers to the common welfare.

Mrs. M. L. Matthews: The author says that the safety of the future depends on the well-directed effort of men of wide and clear vision contriving to increase the common good. I have seen this gift of vision described as the "spirit of progress"—defined as "the desire to know what constitutes true success and the willingness to take the patient steps which lead to it; the desire to correct errors, traits and tendencies which retard progress and the willingness to receive new ideas and to act upon them; the desire to act from sound motives and the willingness to give up false and temporary success for vital growth; the eagerness to utilize every wholesome opportunity; the enthusiasm to strive for excellence for its own sake and the energy to push on, pausing only when the victory is won." The author says: "The nation desires each of its members to have the fullest opportunity of self-expression." If we have wisdom and knowledge enough to express our best selves, how good it is. Nowadays, however, the term "self-expression" takes the place of that good old-fashioned term "self-sacrifice." One wonders how much of the industrial unrest of our time is the result of a mistaken clamour for self-expression when life and the world and service never called more insistently for self-sacrifice. How frequently one hears the obvious shirking of a duty for more congenial effort expressed as a fulfilling of the need for self-expression. And yet the whole due and duty of man, whether engineer or artisan, poet, priest or peasant, cannot be expressed in terms of self-expression or self-sacrifice; in fact until we proceed a step further than self, i.e. to future generations, whether as workers or as a people, we shall not grasp the meaning of life, nor its message, nor its fullness. It is well-expressed in this thought from Ruskin: "God has lent us the earth for our life; it is a great entail. It belongs as much to those who are to come after us and whose names are already written in the book of creation as to us; and we have no right, by anything we do or neglect, to involve them in unnecessary penalties, or deprive them of benefits which it is in our power to bequeath. And this the more, because it is one of the appointed conditions of the labour of men that, in proportion to the time between the seed-sowing and the harvest is the fulness of the fruit; and that generally, therefore, the farther off we place our aim, and the less we desire to be ourselves the witness of what we have laboured for, the more wide and rich will be the measure of our success." Whilst then, it is the *due* of the engineer to reap his full of the harvest his work and talent have brought him in the present age, let him keep well in mind that the *duty* and privilege of caring truly for the future of engineering

and the engineer is his: and this he may secure most adequately in "finding the engineer." I suppose that the ideal is still that a profession or business should pass from father to son, and where it is practicable to give a schoolboy with a turn for engineering a certain judicious freedom of the works the results can be most beneficial in after-life. Youngsters, before that age of self-consciousness creeps on, get an insight into the hearts and lives of the workers that is never granted them in later years and may stand them in good stead in after days. Impressions of work, processes and methods are subconsciously absorbed in interested watchings of some one of youth's ideal heroes of toil while much of interest is shown them that would be kept from more experienced eyes. Then it should be the pleasant duty of the older man to choose out the promising youngster and give a wise and helping hand in his career. As in stock rearing, it is not the man who can choose the champion when it is priced at 1 000 guineas who has the insight of genius but the man who can pick it out in the rough and turn it out, through training and competent handling, the unbeaten pride of the show ring. And so the man who is a judge of men and character should be able to mark and select the coming man and handle and train him for his future good and the good of engineering. If such a man have faith in his own destiny, he will find no fear in this. The author recommends the study of the great writers and poets in order to obtain a sense of the fitness of words, and then gives some valuable advice in this respect. I would firmly endorse this and recommend their study as an aid to right thinking, wisdom and general guidance. It is a strange and regrettable fact that at the time when it would be most helpful in a young man's career there is, if not a positive distaste, a decided disinclination on the part of youth for the literature which contains the helpful and thoughtful advice from the rich experience of the master minds, who have found the real road to success in the true things of life, spiritually and materially. For though youth would chiefly benefit by its perusal, it is often the older man who best appreciates such literature; because if he has himself, however haltingly, endeavoured to walk in the straight paths of wisdom, experience enables him to enter into its truths; though he is always conscious of an underlying regret that this taste for good literature did not come to him in the morning rather than in the evening of life. If youth would but realize it, success is for him if he will not fear to dig deep down into the true and lasting things of life. Thirty minutes or an hour a day spent with the master thinkers will provide him with a treasure house upon which to draw as the years pass. A man may be called upon to speak at a moment's notice. If he speaks well it is because he draws from a storehouse of well-nourished thoughts and impressions garnered throughout the years. Men's careers have been marred by basing their action on unsound theories of life and business, and a change from a wrong thought to a right thought may open his eyes to a broader field of opportunity and activity. Thoreau says, "I know of no more encouraging fact than the unquestioning ability of a man to elevate his life by conscious endeavour." More sure than anything else is the value of a right thought. If a man will be positive, a personality and not merely a person, let his thoughts be straight and true. Thought is a creative force. And even as an engineer designs his masterpiece first in thought, so a man may design his life that it may be built four-square, by taking heed to his thoughts. Let him hold firmly in mind his ideal of what he would be, water it continually with confident assurance of achievement, do faithfully and well his present duty, however far it may seem from his ultimate hope, and he shall achieve miracles; and the greatest miracle will be that the good has come by such natural means that when it comes it seems no miracle, but something that was bound to happen. There is not a successful man to-day who cannot look at some achievement in his life that is not more than he at one part of his career could ever have dreamed. Whether he realizes it or not, a man's whole career depends on his attitude of mind, whether it is straight and clear and sound. Give the young engineer a sound, true mind in that sound young body of his, and his due, his duty and his future are well assured. And if there be one who has not yet learned how good it is to lean in faith on our All-Wise Father, this for his consideration and the good of engineering: "In the darkest hour through which a human soul can pass, whatever else is doubtful, this at least is certain. If there be no God and no future state, yet, even then, it is better to be generous than selfish, better to be chaste than licentious, better to be true than false, better to be brave than to be a coward. Blessed beyond all earthly blessedness is the man who in the tempestuous darkness of the soul, has dared to hold fast to these venerable landmarks. Thrice blessed is he who, when all is drear and cheerless within and without, when his teachers terrify him and his friends shrink from him, has obstinately clung to moral good. Thrice blessed, because his night shall pass into clear, bright day." (FREDERICK WILLIAM ROBERTSON.)

Mr. B. O. Anson: There are many of us who think that there is something wrong with engineering, and particularly electrical engineering. It is difficult to diagnose the complaint and to ascertain exactly what is the remedy. A few years ago I attended a dinner at which Mr. Atkinson, who was then President of the Institution, made a speech in which he recounted certain failings in the development of electric lighting, referred to delays on the telegraph and mentioned the costliness of the telephone in this country. The burden of his speech, however, was that although it is necessary for engineers to push forward with vigour, it was not to be assumed that the fault of the present state of affairs is always with the engineer and he used the expression: ". . . we engineers are in some way or another being cheated of our victory over time and space." In my opinion that summarizes the situation exactly and it is for us as engineers to discover the reason. Amongst other things I think we may say that there is a feeling amongst business men and administrators generally that engineers are not competent to occupy big posts. Lord Balfour on one occasion said that one of the most difficult tasks he had at the Admiralty was to reconcile the conflicting opinions of

experts. Other eminent people have made similar statements, and we as engineers have to challenge the general impression that is evidently abroad that people who are experts are, of necessity, unsuitable to be general managers or managing directors. Perhaps I might be permitted to read an extract from an article that appeared in the Commercial Supplement to *The Manchester Guardian* of the 5th November. This article was written by a cost accountant on the subject of cost accounting, and the importance of this subject was enlarged upon. I suppose that, as engineers, we all appreciate the importance of cost accounting, but it is hardly likely that we shall appreciate the following: "The training received by a cost accountant, and his necessary habit of bringing every business problem down to bedrock fact, has made some of the most progressive firms in the country take the logical step of making the cost accountant a director. And when one thinks of it there can scarcely be any better school for directors than that of really thorough cost accountancy. It enables a man to see a business steadily and to see it whole, which is just what the ordinary technical man, by virtue of his technical training, cannot do. And also, unlike the technical man, the cost accountant has no axe to grind; he is not personally implicated in conclusions, and is not tempted to avoid them because they are unpleasant." The announcement of this article was placarded all over London three weeks ago, and it was evidently regarded by *The Manchester Guardian* as one of considerable importance. The point I want to make is that engineers are not regarded as suitable individuals to occupy high business positions. It is no doubt well known that the Civil Service is controlled by a body of men known as administrative officers. These officials occupy practically all the highest posts in the Civil Service, and in many Government Departments a large amount of work is of an engineering or highly technical character. It is a very rare occurrence for engineering officers to occupy these high administrative posts. I think that the time has come when engineers generally should make a special point of developing themselves by special business training and engaging in public propaganda so that they will more naturally fall into higher positions than they do to-day. Considering the great effect of engineering on modern civilization, it is inevitable that in course of time more and more of an engineering atmosphere will drift into the general business world, and it seems that engineers will have to meet the position and even to follow the example of lawyers and take their place in the House of Commons. It is perhaps not too much to say that eventually the engineer must fight the lawyer for the control of the country.

Mr. P. Dunsheath: I imagine that the Papers Committee may have had some misgivings about accepting a paper so unorthodox as this. Though not a long paper, it is packed with valuable, inspiring and original suggestions for all engineers, and I think that I shall not be alone in reading it again and again. To take one small point in the paper, the author advocates flexibility of ideas. How important this is, but how very rarely is it appreciated. In my own particular branch of engineering—research—I find it very necessary to impress on my colleagues the fact that because they believed a certain thing 12 months ago there is no reason for their still continuing to believe it. It is surprising how people object to changing their views. The author's comment on the choice of words should be read by all engineers who have to write specifications or reports or letters. It seems to me that what we really lack is simplicity of language. We should not say "The answer is in the negative" but simply "No." The author says "If we let a child live, we must in decency see that no great unclimbable rocks are left lying in his path." I agree with the author's treatment of that point, but I think that the metaphor is dangerous as he uses it. It suggests that we must remove difficulties, but I think the whole spirit of this paper is that character is formed by difficulties. There is far too great a tendency to-day to smooth the path for everybody, with the result that initiative is destroyed and the prosperity of the community suffers. I do not think we should preach comfort too much. That which appears unclimbable to-day will not be so to-morrow, and in this connection I should just like to quote some words of J. J. Stephens: "He finds out what he cannot do and then he goes and does it." With regard to the Section dealing with the finding of engineers, I think that the author's remarks are very well illustrated by what happened in the recent war. Technical units frequently had to draft into themselves men who were not engineers and it was very surprising and interesting to notice the natural way in which a man, who had never done engineering in his ordinary commercial life, took to it. I knew a case of a lawyer who was so drafted and who was put on engineering jobs; he did them in a far better way than many trained engineers. Of course, on the other hand, many of those temporary engineers were utter failures. I am rather dubious about leaving the question of selection to schoolmasters. I do not think there are many schoolmasters who really understand what makes a successful engineer. There is some truth in Bernard Shaw's gibe: "He who can, does. He who cannot, teaches." I think the best way of dealing with the matter would be for certain men with insight, such as the author, to set up as consultants. Parents would surely willingly pay adequate fees for a consultation on what to do with their boys.

Mr. W. J. John: As a teacher of engineering I am chiefly interested in Sections (3) and (4) of the paper, namely the finding and training of engineers. To the teacher at the engineering college come young men who have recently decided that they are to take up engineering as a profession, and it is the teacher perhaps, more than anyone else, who realizes how tremendously important it is that they should be fitted by natural aptitude for the profession they have chosen. In my opinion one important matter has not received in this paper the consideration which is its due. Suppose a class at an engineering college is carefully and successfully selected by vocational tests. Suppose further that the curriculum to which they are trained is that given on page 196. On whom does the success of the training depend in its entirety? It depends on the professors and lecturers —the teaching staff at the college. When the training

of engineers is being discussed, I think this side of it should receive consideration, and there are one or two points I should like to put forward. In my opinion the engineers who comprise the teaching staff at an engineering college are separated by too wide a gulf from their brother engineers in works. As a consequence I am afraid that to many students there must be a rather artificial air about college engineering. It is hard for them to believe that when they enter the college they are being trained to become engineers and that it is not all a continuation of school. Things are so similar—lecture rooms and teachers—blackboards and chalk. There is not sufficient smell of oil, not sufficient rumbling of machines. The gulf, in my opinion, can only be successfully bridged by the lecturer. He must make the students realize the actuality of the work they are doing, which one day will be made concrete in terms of steel and copper. Knowing something of the psychology of the ordinary student, I say that the influence of the lecturer will be much more potent, his power to bridge the gulf greatly enhanced, if the word goes round "He has just come back from the engineering works of Messrs. So and So." He will seem a real engineer to them then. Would the young doctor being trained at a hospital have so much confidence in his lecturers if he knew they were only telling him how to carry out a dangerous operation and could not actually do the thing themselves? Should not then the lecturer on, say, electrical power be able to carry through the technical calculations involved in supplying a community with power and light as well as a brother engineer who earns his daily bread by so doing? Should not the lecturer in electrical machine design be able to design a generator or transformer or rotary converter which would be approved of by the specialist designer in the works? Surely lecturers ought to be able to do what they talk about doing. There must be a limit, of course, to what is expected of a lecturer, but much more could reasonably be expected of him if more were done to help in fitting him for his great task. I believe that a scheme such as I outline now is quite feasible and would produce good results. It is not new, but the importance of it renders an apology unnecessary for introducing it here. The college authorities should give engineering lecturers one year's leave in four; three years at college, one year on leave. The engineering manufacturers of the country should be prepared to give the lecturer an executive post in a works during his leave and allow him special facilities to make himself fully conversant with the latest practice. I know of no single thing which would more positively improve engineering training as given at the colleges than this scheme where special provision is made for keeping engineering lecturers fully abreast of the latest practice in their subject. The cost of this suggested innovation would be trifling. Its results would be considerable. With lecturers such as these would be, the specially selected students would reap fuller benefit from their training. The lecturer would be the link between college and works; keeping in touch with both and removing a little of the troublesome make-believe from the engineering lectures, making his subject at college a living one illustrated by examples from current engineering practice and not from that of a decade ago. All the splendid work which may be done as regards selecting the right men to be engineers, and the correct curriculum to which they are to be trained, will not have its full value unless attention is given to the problem of selecting the right men to teach them at the training colleges, and then giving these men an opportunity to keep abreast of current engineering practice as a complement to their acquirement of ripe teaching experience as the years roll on. The paper contains one sentence which appeals to me very particularly; it is this: "All the more then must a young man be thankful now if he can find an older man with knowledge willing to take his hand and lead him on." It was my good fortune when I left college to become the author's assistant. In him I found the older man with knowledge and I have never forgotten how well and how patiently he led me on. I do my best to repay that great debt now—not to him, that debt in the nature of things I can never repay. But I am now myself an older man with some knowledge, and to the younger man I try to hold out a helping hand. It is the one way I can repay the great debt I, personally, owe to the author.

Mr. D. G. Hurlbatt: I still think that overseas work in particular is not yet so highly civilized and therefore specializable as to render incorrect the old saying "an ounce of practice is worth a ton of theory." There are many people who can rise to important, well paid and highly useful positions mainly through practical and not academic experience. In view of the present hopeless state of affairs in England, I think that this paper should be sent to all the well-known teachers in this country, and also to all professions, Members of Parliament, and industrialists. I feel that the paper should not have been first read from the rostrum of an engineers' organization. The engineering profession is associated, in the public fancy, with hard ways, hard blows, hard deals and hard words. The engineer gets his due vastly more in the United States than elsewhere, especially the United Kingdom, hence the greater prosperity of the States. I do not think that the English engineer pays less attention to duty than does the American engineer, but he gets less chance and encouragement, owing to the lower ideals of the politicians in this country. I hope that most of the author's ideas will prevail in the future. This is not a "quick" country, but it is not so "dead" as many seem to think, and this little pill with its various coatings (as we may term the criticisms) in repeated doses will not do Englishmen any harm. It seems a pity that big annual events like the I.M.E.A. Convention cannot be made even bigger—more collective—and include, for two or three days at least, fair-sized deputations from each and every profession, etc., and also a large deputation of Members of Parliament, when such pills could be swallowed in pleasant, useful, collaborative unison, with more effective results. It seems cruel to criticize such a poetic simile as that on page 200, but a loom has to be driven and its output distributed. From the tone of the whole paper I should guess, perhaps wrongly, that the author favours the group drive, with mass consumption for use, and not the individual, personal-gain, motor, so to speak. As for aiming too high, it is certainly better to give than

to receive, but the margin of ideal here seems rather on the high side in this respect, and also in everyday life now for engineers.

Mr. E. Kilburn Scott: Some time ago Mr. Hilaire Belloc said that the way to carry out reforms was for a determined group deliberately to set to work to "capture the executive," by which he meant the controlling positions in public and private affairs. As a result of long and rather varied experience, I have come to the conclusion that engineers will be forced to act on this principle. A step in that direction would be the formation of an Engineering Foundation on similar lines to that in America, because by co-ordinating the various engineering and scientific societies of the country, the status of engineers would be raised socially and politically. Records of those now in control show that some are related to the aristocracy, some are financiers, many are members of the legal profession, especially barristers, whilst newspaper proprietors have become menacingly powerful since the war. Almost all these men have been trained on the old classical lines of public schools and older universities, which cultivate the habit of looking back to precedents for guidance. It is peculiarly the habit of mind of members of the legal profession. Scientists, engineers, chemists, and especially electrical engineers, have completely changed the art of living, even as compared with the last century, and therefore the men who are required for executive control should have the scientific, forward-looking minds which arrive at decisions by reasoning and research. For a long time the classically trained have been out of their depth, and as scientific and engineering progress speeds up, they get further behind every day. They must inevitably drop out of the running, in which case the scientifically trained will have an opportunity of taking their places. For some years it has been my duty to teach young engineers who were just about to leave college, and I always found some in every class who had social and other qualifications that fitted them for leadership and for public life. Such men should be encouraged to take part in civic affairs in addition to their engineering work, because by doing so there will in time grow up a body of scientifically trained men who have also the experience to take any position in national affairs. Unfortunately, some teachers of science and even of engineering are more academic than practical, and by lectures and freak examination questions divert the attention of some students to mathematical gymnastics. It interferes with their gaining the intimate knowledge of human nature that follows from learning the handicrafts of engineering work. Engineering experience in workshops and on outside constructional work is of tremendous advantage from the point of view of training leaders, and it is beyond compare better than the knowledge gained from books in professions such as law and accountancy. By working as bench mates with workmen, engineers get the first-hand information of human nature which enables them successfully to handle people in any situation. I am firmly of opinion that a great deal of unrest in industrial affairs is due to individuals being placed in executive and political positions for which they have no training or real sympathy. It is nothing short of disgraceful that there are concerns in this country, wholly or partly engineering in character, which have on their directorates lawyers, accountants, retired soldiers, promoted book-keepers, and company promoters. One often hears the parrot-cry that business men are necessary in engineering, but my experience of the business men so-called who batten on the engineering profession and especially on inventive engineers is that their main characteristic is a species of "low cunning." Why is it that several English firms are making hundreds of electric locomotives for use on railways in Argentine, France, India, Japan, etc., and that so few are being made for railways of this country? It is because the men in control of our railways have no first-hand knowledge of electric traction. Consider how the situation would be changed if on the directorate of each railway company there were men with working knowledge of electric traction. Why should there not be at least one electrical engineer on the directorate of every engineering concern in the country? Wherever electrical power has made headway in a particular industry it will be found that it was because some younger man with electrical engineering knowledge has got into a controlling position as manager or director. That is what I mean by saying that it is high time that engineers should set out deliberately to "capture the executive" whenever and wherever they can. An example of retarding engineering progress is to be seen at Lots Road power house, where 64 old boilers are used for raising steam, when about a dozen boilers of modern design could do the work much more efficiently. From the point of view of boiler makers who supply spare parts, it has been good business, but it is poor engineering to have such an ancient boiler plant in existence at the present time. In the Dominions and the United States, where engineering concerns are controlled by engineers, such inefficient boilers would have been scrapped long ago. My experience as a resident in Australia and the United States leads me to say that if we are to maintain this country as an engineering centre we shall have to go in for the scrapping habit a good deal more. There are men in this and other engineering Institutions who are excellently equipped, not only to direct engineering concerns, but also to lead in affairs which are not of that nature. Some have managed to capture positions already. I have in mind a consulting electrical engineer who, after electrifying a cement works, was asked to join the board, and as a result of his executive ability in that position is now managing director of the concern and some others. It is quite possible that such members of the Institution as are fitted for public life will have to be "boosted" into it because they are modest, or they wish to live the "quiet life," but the other members must encourage them to take such positions and if necessary work for them to get in.

(*Communicated*): At the meeting when the paper was discussed, I referred to one who would make an ideal Member of Parliament if he could only be persuaded to try. I say that, because he started his engineering career in a steam locomotive works, then designed mining machinery which brought him into close touch with miners, and subsequently, as head of a large electric manufacturing Association, had to attend to

negotiations of high finance and the personnel of many works. Even his recreation is farming. There are many men of wide experience of everyday affairs in the Institutions. Engineers who are fitted for public life should enter it as a duty to the profession and to themselves. All who have had to attend the hearing of Bills more or less connected with engineering in committee rooms of the Houses of Parliament know of the great waste of public money in paying parliamentary agents, barristers, town clerks, etc., and great waste of time in trying to teach members of such committees who have no technical knowledge. Engineering progress in this country has for years been retarded by inquiries, and talk before committees and commissions, largely made up of men without technical knowledge. It is necessary for the engineering profession to be largely represented in Parliament, because there are many matters connected with the development of national resources, the patent laws, etc., which cry aloud for attention by scientifically-minded men, and especially engineers.

[The author's reply to this discussion will be found on page 229.]

Mersey and North Wales (Liverpool) Centre, at Liverpool, 16 November, 1925.

Prof. E. W. Marchant: I am particularly interested in what the author says about the efforts that have been made by schoolmasters, in particular Dr. Johnston of Highgate, in attempting to select suitable vocations for boys, and training them more or less vocationally. I think that the results to be obtained by this method are rather limited in the case of a large number of boys. The plan undoubtedly works well in the case of boys with very strong natural inclinations, but I have come to the conclusion that a large proportion of boys at the school age have no very definite inclinations—they will go one way or another according to the direction in which they are encouraged to go. The most famous of the "vocational" schoolmasters was Sanderson of Oundle, with whom I had the good fortune to discuss this matter on several occasions. He had very strong views indeed. He started with the assumption that every boy has a very definite vocation in life, and that it was the duty of the schoolmaster to find it out. (I think he was the schoolmaster in Wells's "Undying Fire.") After some experience of the practical working of this system I have come to the conclusion that it is impossible to say definitely in the case of a very large majority of boys when they are of school age, which is the best vocation for them to fill. There is another factor which should be taken into account when vocations are to be chosen. Although it is referred to in the paper, that is a point on which I do not think sufficient stress has been laid. A schoolmaster cannot say, "I have here a certain number of boys; these are to be engineers, and those are to be something else," and so on. I think that it is necessary to study the possibilities of employment. It is no good dividing the boys of a school altogether in accordance with their inclinations. There may be a preponderance of boys in one direction or the other, and I think a great deal is to be done, and should be done by schools and universities, in trying to exercise this kind of selection. It is necessary so to train boys that they will fulfil the needs of the community. That is a point which we have had very much before us in the Liverpool University, i.e. to try to turn out boys who will find occupation when their training is completed. There is another point. A great deal of any man's life is occupied in uncongenial employment. I think we all have to spend a lot of time in doing things that we do not care about, and I think, therefore, that a great deal is to be said in favour of the exact opposite of the plan which Dr. Sanderson advocated, that is, to train boys to do things they do not like and to make them work hard at them. If a boy is trained to work hard and do his duty whether it is congenial or uncongenial, then I think that he will be useful wherever he goes. The boy should be given the idea that he is in the world to serve his fellows and not merely to make his own living. It may be said that that is rather an unpractical point of view, but I think it is very important. If an engineer sets out in life with the idea of making his fortune I do not think he will give his best service to the world, but if he recognizes that all he does is of service to the community, and that his work is of the greatest value when it does the greatest service, he will become a much more useful member of society. I am encouraged to quote the last four lines of one of Kipling's poems:—

> "If you can fill the unforgiving minute
> With sixty seconds' worth of distance run,
> Yours is the world and everything that's in it
> And, which is more, you'll be a man, my son."

Mr. J. A. Moreton: I do not share the author's fear that so-called free education, etc., is demoralizing. As a matter of fact these things are not really free at all; we pay for them as citizens in our rates and taxes, and we have the right, without feeling demoralized, to draw on all these fundamental things that are provided by ourselves as a community. If we had each to provide them individually we should never have time to practise our own profession. The author says that some are born engineers, and that others have engineering thrust upon them. I feel doubtful about the born-genius attitude to a particular profession. My experience is that a man who has a fairly good class of mind and has had a good general education will make a useful engineer or useful anything else. The author suggests that we should compel certain people to enter the engineering profession. It is not, I think, very easy or desirable to do this, and who is to be the judge? I should say to a young man: "If you want interesting and hard work and anxiety, be an engineer, but if you want to make money you had better be a shopkeeper." I quite agree with the author that it is useful to have a good knowledge of literature. Coming to the last part of the paper, it is quite true that we engineers have much to teach others and it is good, of course, to be able to teach,

but it is better to be able to learn, and we need not become too proud because we can teach. I often wonder whether an engineer or a dustman is of the more real value to society. The author says that engineers have made life complex, and it is true that machinery has become in some ways a Frankenstein monster. It gets out of control and, instead of us running it, it runs us. We have invented all sorts of machines which kill people indiscriminately without being meant to do so. The engineer has a further duty as a member of society and his responsibility cannot cease when he has made the machine; he must take his part in controlling its proper use in society's service. The dustman at any rate does not invent things which will kill people: he saves us from death in the form of fever and pestilence. So that although we are undoubtedly clever we may as well be humble about it. As Michael Faraday said, "The education of the judgment has for its first and last step—humility."

Prof. C. O. Bannister: Every instructor of engineering subjects should study the paper, and also every student and every schoolmaster who has boys under him who will eventually become engineers. I am not quite in agreement with the author's view in regard to compelling boys to enter the engineering profession and I think that the first sentence on page 195 should read: "We also let some escape into other professions who should be encouraged to come into engineering." The most difficult children to deal with from a career point of view are undoubtedly those who show no indication of interest in some special calling, and it is the parents' and teachers' duty to study these cases and if possible to develop some definite interest. Dr. Johnston has certainly gone further than most schoolmasters in this direction and it is to be hoped that his methods will be more largely used and developed. It is a comparatively simple matter to distinguish a boy with a decidedly engineering or scientific bent from a boy with a decidedly literary or artistic bent, but unfortunately there are many cases in which no definite aptitude can be discovered, and these require special study and guidance. With regard to the training of engineers, there is much to be said in favour of students obtaining an insight into works methods in the early days of their study, in order to enable them to learn something of the application of the principles involved at the time they are learning those principles. In this connection the arrangements made at the Liverpool University for vacation voyages and works experience are most valuable. The scope of the training, as given on page 196, etc., considered necessary for engineers at first somewhat alarmed me, in view of our own fairly full time tables; on second thought, however, I realized that if the types of instruction mentioned in Section A were correctly given, they would inevitably be associated with the development of the virtues and graces mentioned in Section B. This is undoubtedly the case with students who take an active part in sports, student societies, etc. I recently learnt from an American who had visited England to study our methods of training engineers, that engineering courses are being largely followed in America by students who do not intend to become engineers but who are going into banks, insurance companies, large business houses, etc. On page 197 the author pleads for a varied experience; I always make a point of advising undergraduates and young engineers to take advantage of every opportunity of widening their experience and in many cases to make a change in their occupation, even if this does not carry an increase of pay. From a recent experience I can substantiate what the author says in regard to writing. In connection with a recent vacancy I received applications from several graduates I had previously met as their external examiner, and the written applications of several men with good knowledge and good degrees were most disappointing and were sufficiently bad to render even an interview unnecessary. My own experience is that men who are educated in boarding schools or who have had to leave home for their college courses are the best letter writers, possibly because they have had more practice at this important art.

Mr. C. Rettie: On page 196, items (5) and (6) deal with "Infusion of fairness, unselfishness, tolerance, etc.," and "Formation of friendships." In my present occupation I am working side by side with university men who are well educated and have won degrees, and whilst some of them are always willing and very patient to help me in the problems in which I am interested, there are others who are not so willing. I am interested in the abstract theory of the steam turbine and in connection with this theory there is a very interesting problem on the weight of the steam when it leaves the nozzle, described in H. M. Martin's pamphlet on "The New Theory of the Steam Turbine," published by *Engineering*. I tried to get one of our university men into a discussion on this problem, but because I did not understand a mathematical problem in the middle of the paper I was not successful. I think that that is a wrong attitude to take and I make this appeal to the younger generation to have more patience with their elders who have not had the chances of a better education such as is available to-day.

Mr. E. W. Ashby: The author, in his remarks on accuracy of expression, utters a warning to would-be critics. In finding engineers (see Section 3) considerable caution is desirable. A scholar may excel for the time being in a particular subject solely because of the way in which it is presented to him; or conversely he may *appear* unfitted for a certain occupation—although actually his natural tendencies lie in that direction—because he is repelled by the teacher's handling of the subject. My personal experience is that wherever advice or information is sought—in the drawing office or in the works, from designer or mechanic—it is given freely. Obviously tact is essential in the search for information. I cannot agree with the suggestion that boys living at home during their later education are likely to be less proficient correspondents. Taking part in the general topical conversation at home, the student is far more likely to develop powers of expression than he would be when exploring the rather limited range of subjects available for discussion and correspondence as a boarder.

Mr. A. Wynne-Jones: This paper bears on every page evidence of wide reading and deep culture, and contains references to authors of widely different char-

acter. This appears to me to be the side of an engineer's education which is often neglected. Among my colleagues I cannot recall one with whom, so far as I know, I could discuss the beauty and profundity of Shakespeare, or with whom I could discuss astronomy, or languages; and I feel it has been a great loss to me. Prof. Marchant in the course of his remarks quoted, half-apologetically, a verse of poetry from Kipling, but I do not think that any man need be ashamed of having a taste for poetry. The study of literature has an effect on the mind which enables us to deal more easily with the problems of life. The author shows that he has also the faculty of humour —the most precious gift of the gods. It is for that reason that I think he has not done himself justice in the first paragraph, in which he hints at the lethal chamber for the innumerable company who are not doing their best. I think this is rather drastic, and I would anxiously inquire, if every man who is not pulling his weight is to be dealt with in this drastic fashion, what is to become of us?

Mr. W. G. Taylor: It is not often that an engineer comes forward and speaks about these matters in such an able manner as the author has done. This is probably because the art of easy speech in public is given to but few of us. Engineers are apt to become so absorbed in their own business that they do not enter public life to the extent which is desirable. If it were possible to achieve adequate representation of the engineering profession in municipal and national political circles there is no doubt but that the community in general would benefit and the technical man would acquire greater facility in the public presentation of his views. In a paper of this character there is much matter for discussion, and I should like to put forward a few points for consideration. The author has stated that "the confines of our ignorance are not so narrow as they were and the darkness still to be searched is less terrifying than once it seemed." I am not at all sure that "terrifying" is the right word to use in this connection and would rather say "awful," but it seems to me that the wider our knowledge the greater our awe at the spreading field to be explored. I do not understand why the author should recommend the removal of great unclimbable rocks from the path of a child. If a rock is unclimbable it could hardly be removed. However, is it not a good thing for a child to encounter rocks to prove its mettle and assist in the formation of character? It seems to me that the path of the modern child is made too smooth and that the child's future is jeopardized thereby. Certainly the route should be blazed and the helping hand ready, but initial effort by the child should be stimulated. The author, in referring to the loss sustained by the world through the war in which so many able men were killed, mentions "their departure to the place from which no word of these things comes back." Does he not believe that that place is the source of all inspiration? In advocating entrance into public life of specially suitable men one wishes that mention had been made of the body which at the present time is urging the claims of the engineer to be heard as an authority on industrial problems of the day—I refer to the Society of Technical Engineers. It is the duty of every engineer to realize his responsibilities to his profession and country, then to put his shoulder to the wheel—that way lies happiness.

Prof. C. E. Scholes: To those engaged in training engineers on the academical side the paper is full of interesting and provocative points. The definition of a civil engineer drawn up by the Institution of Civil Engineers in 1828 and given on page 194 has been the standard definition in this country for nearly a century. The definition of "engineering" drawn up by the American Society of Mechanical Engineers some 10 years ago is as follows: "Engineering is the science of controlling the forces and utilizing the materials of nature for the benefit of man, and is the art of directing and organizing human activities in connection therewith." To my mind this later definition has much to commend it since it suggests that the engineer has not only to control the sources of power but to utilize the materials in nature and, furthermore, to be responsible for the successful direction and organization of the human element involved. The author has raised an interesting point in the suggestion that a much wider attempt should be made to find engineers by observation of the characteristics of boys at school. I think that the problem is one of considerable difficulty and that the suggested method is open to question. Presumably the decision as to whether or not a boy should be trained as an engineer is to be made at a comparatively early age, but this appears to me to be a great weakness in the scheme. The average boy is a mass of independent variables and it is, I feel, an impossibility to predict the line of his future development. Another factor which must be taken into account is the rate of development of the boy. Some boys mature slowly and their early training gives little or no indication of their future ability. Other boys are precocious and in some cases their early brilliance dies away, leaving them as a spent force with a capacity and intelligence which compares unfavourably with those who have developed more slowly but with greater sureness. In academic life the case of the student who matures slowly is not infrequent, and teachers are familiar with many such students who have developed into first-rate engineers. The scheme suggested would probably prevent the entry of such students into the engineering profession, which would be the loser thereby. The syllabus of a suitable academic engineering training given on page 196 agrees very closely with the training given in the Liverpool University, the only omission here being the instruction and training in hygienics. This may be a desirable feature, but, as Prof. Bannister has already said, the difficulty in arranging a suitable course is the wealth of material and the limited amount of time available. It is not so much a matter of deciding what to put in as to being reconciled to the amount which has to be left out. I think that the academic training of engineers of all branches should consist mainly of the teaching of fundamental principles and that the specialization allowed should be a minimum consistent with the preparation needed for the branch of engineering chosen. As one engaged in this training of engineers I should like to say that the academic training is only one factor, and to stress the importance of the other factors which are essential. No amount of genius or technical ability will

compensate for the lack of character, personality and loyalty. What the world requires and what is best for the engineering profession is the steady supply of trained men of character and courage who, whatever their talents may be, use them to the best advantage and who, because of their character, are trustworthy and loyal. Academic or technical training is a valuable asset, since it enables a man to use his brains and to think clearly, but for the best results this training must be associated with a stable character, honesty of purpose and the desire to do the right thing. Mention has been made by a previous speaker in this discussion, as well as by the author, of the inability of students to write clearly. In spite of repeated efforts made to get students to see the value of this accomplishment, many fail to appreciate the necessity for cultivating the art. In courses where a large amount of laboratory work is done the writing up of the laboratory record book, if done intelligently and consistently, very much improves the style and ability of the student to write reports and this is probably one of the most useful ways of acquiring the art of expressing oneself in writing.

[The author's reply to this discussion will be found on page 229.]

North-Eastern Centre, at Newcastle, 23 November, 1925.

Mr. C. Turnbull: The paper gives us a timely reminder that we are citizens first and that it is our privilege and duty to use our energies for the good of the State. Engineers often keep out of politics because they feel that politicians give too much thought to getting the better of the other party, but there is great need that they should interest themselves in all that pertains to the State to bring about good results there without troubling as to which party is to receive the reward. When we study history we find that historians have a peculiar method of giving to rulers the praise which really belongs to the men who carried out engineering work. The Roman Empire became possible by reason of its roads, bridges, aqueducts and engineering work generally, whilst the British Empire has also come into being largely through the work of its engineers. Much work yet lies at our hands which engineers can carry through if they set themselves to the task. We still waste a year on our childrens' lives in fogging their brains with our jumble of weights and measures. Lord Kelvin said that these were brain-destroying, but I used to think that this was an exaggeration until I recently read some school arithmetics, when I was astonished to find what a muddle the whole thing is. Not only is the jumble useless, but it hinders us from trading with other nations. The time has come when the engineering world should make up its mind to give up this relic of barbarism, and to adopt the simple metric system, so putting us on an equal footing with other nations. I should also like to recall the late Mr. Wordingham's proposals for the improvement of the Institution by the creation of additional departments of activity. The educational department is greatly needed; it would help our textbook writers by guiding them in the teaching of pupils. Our textbooks could well afford to omit many of the absurd problems which now cumber them, whilst they could very well develop many useful ideas which now are neglected. For example, one engineering textbook asks its readers to calculate the time taken for a large tank of water to empty itself through a hole, and gives the result to a hundredth part of a second, although in actual practice the tank would drip for half an hour or so. An educational committee would save students from that kind of thing, and also help textbook writers to deal with points which are necessary to the engineer in his future career.

Mr. W. T. Maccall: There is one phrase in the paper that appears to require further explanation to avoid misunderstanding, viz. "the importance of not doing things ourselves if we can find someone to do them well for us." As it stands, it is rather reminiscent of the perverted proverb: "Never do to-day what you may get someone else to do to-morrow." I am in agreement, however, with the author's real meaning, which I take to be that as soon as a man reaches a position of the least responsibility it is important to realize the necessity of leaving some things to other people, even if he can do them better himself. Otherwise the time comes when they have to be so left, and the result may be disastrous if the deputies have not had any previous experience of such work. With regard to the "finding of engineers," any satisfactory test would be most valuable. The present difficulty is that when a boy has once started on a course of training for engineering or any other profession it is often impossible to change over to a different one. Once I came across a youth who, after a three-year full-time day course in a university, gave up engineering because it was too dirty. He might have found this out sooner, but on the other hand the majority who had reached that stage would carry on even if they had an equally strong dislike of dirt. Another reason that enhances the value of the early testing of aptitudes is the greater length of present-day training. And though the training will in no case be thrown away entirely, as engineering knowledge is always useful, it is still of great importance throughout the course of training, whether in works or in college, to test the suitability of the youth for higher work. Examinations may not be ideal for this purpose, but when conducted by the teachers (works or college) they are a very useful test. With the author's remarks on the actual training I am in general agreement, but I should like to emphasize certain points. One is that the memorizing of results alone is very poor training—what is wanted more is the knowledge of where to find certain things when they are needed, and of the methods to use in tackling new problems when they arise. Another is the importance of being able to use words well, and hence the value of literary training, even when it has no direct bearing on engineering. A third is the advantage of mixing with all classes, so as to be able to deal with the human problems that arise. And a

fourth, which I wish to stress particularly, is the benefit to be derived from travelling in other countries, especially in youth, as was realized in other connections when "the grand tour" was an essential part of every gentleman's training. Finally, I should like to suggest that an important aid to "the finding of engineers" would be to remove the financial barrier by the provision of further suitable scholarships. But, to quote from my address last year as chairman of this Section, this should be accompanied by tests to prevent costly education from being wasted on unsuitable students.

Mr. A. W. Crompton: It will be agreed that, apart from an occasional Presidential or Chairman's Address, the many very important matters with which the average member of the Institution is vitally concerned have not had that prominence and consideration given to them which they deserve. Even when such addresses have been delivered their full benefit has not in general been received, since no opportunity has arisen for discussion and as a rule they have only to be read at one meeting. It may, however, be within the memory of some members present that the Institution has, as a body, appreciated the necessity for engineers to take steps to secure due monetary recognition of their services. It may be of interest, therefore, to quote in this connection the following resolution passed at a Council Meeting held on the 17th October, 1918: "That the Council of the Institution of Electrical Engineers officially recognize the Electrical Power Engineers' Association as the protective Association for engineers qualified to hold a responsible position directly concerned with the transmission, distribution or utilization of electrical energy." Since that time the above Association has fully justified its existence and at the present time the final preparations are being made to put into operation a scheme of training which has been formulated after some 3 years in co-operation with the representatives of the various undertakings acting through the National and District Joint Boards (Electricity Supply Industry). It is hoped, as a result of the operation of this scheme, to secure the right type of trainee and to ensure that a sufficient number of qualified men are available to fill in due course the positions of responsibility in the industry which is growing so rapidly. It is proposed to invite the assistance of the Institution particularly in regard to the necessary proficiency tests. I fully agree with the author, however, that technical qualifications are by no means the only requisite of an engineer. His potentialities for evil as well as for good must be realized. The use made of engineers during the recent war is an indication of what might happen in the future, to the loss of the world in general, unless the morality of all engaged in the profession is of the highest. There is, I think, at least one important omission from the author's summary (page 194) of those constituting the Institution, that is the large number concerned with the transmission and distribution of electricity, e.g. mains engineers, etc., and I suggest that the important function of such entitles them to "honourable mention" rather than inclusion in the phrase "many others."

Mr. C. Vernier: Section (1) of the paper contains, perhaps, a greater number of arresting sentences than is usually compressed within any similar number of words. Its general application would, I firmly believe, provide the remedy for our present ills, most of which are derived from ignorance and selfishness. Let us note clearly that the author's remarks in this Section do not apply only to engineers, but to everyone, high and low, rich and poor, in all walks of life. There is no right in this world which, as he remarks, if properly understood does not carry a corresponding duty to others, and the most despicable of all is the man who demands and contrives to filch what he deems to be his rights without thought or consideration of the rights and of the suffering he may cause to others. Yet we see examples of this every day and especially in the mass where, for some strange and inexplicable reason, men in concert with others will act in a way which they would not do or sanction as individuals. For this the responsibility rests chiefly on those who are called upon to be leaders of men, and in such measure as they have received authority it is their duty to exercise it prudently, wisely and to the common good. There is so much contained in this Section that "an unwise man doth not consider and that a fool does not understand" that it would be possible to discuss it further with great advantage. I must only confine myself to endorse and commend the author's statement with but one comment as to the free meals, free education, doles, etc. These, in the present imperfect state of our social and political organization, are essential, and are only harmful in so much that the recipients have never been taught, or have forgotten, or even deny that in such measure as they are accorded them they are in debt to the community. As to doles, much can be forgiven, for the community itself in these post-war years has signally failed in giving to so many who endured untold sacrifices for it during the war the only thing which can bring them contentment and self-respect; that is, honest work. If the hundreds of millions of pounds which have been spent, having as their only result the deterioration, if not demoralization, of some 10 per cent (more or less) of our working population by idleness, had been spent on useful improvements of the country's industrial facilities, such as docks, railways, canals, harbours, electrification, housing and the like, and even if some of these schemes had proved ill-conceived and wasteful, the country would have been immeasurably the richer in the broad sense, and more contented to-day. The community also has its duty towards its members, that is its due to the engineer (and others), but it commonly falls far short of its duty and seldom recognizes its best servants and greatest benefactors, and too often only when they are dead. I do not attach anything like the same importance as the author does to the finding of engineers, and most strongly do I deprecate enlisting the heads of secondary and public schools for their selection. Most of these heads have so little conception of the qualities necessary to make a successful engineer that the suggestion is positively dangerous. "The engineering boy is one of the most difficult to determine." I agree with Dr. Johnston, and only a process of elimination can sort him out

from the rest. Besides, not only do many boys of school age totally fail to reveal much of the engineering aptitude which they do in later years—some develop later than others—but the work of the engineer is so vast in its ramifications as to make it impossible to determine what niche any particular boy may eventually fit into and fill successfully. We have only to look at the few descriptions of electrical engineers given on page 194 as being comprised in our Institution, to see how varied are the qualifications necessary to fill the numerous grades of each of these classes. For the same reason I am of the opinion that our recognized academic training and examinations for engineers leave much to be desired, and are largely wasted except for special positions, of which there are but a very limited number to be filled. Is it really necessary that most of our young men wishing to be engineers should, merely to secure a hall-mark in their profession, strive to spend so many of the most receptive years of their life in the attainment of theoretical knowledge which they will, in many cases, never use in after-life? We have become so unreasonable in educational matters during the last 20 or 30 years that there is now a tendency to shut the door on, or at least make things extremely difficult for, the young engineer who is not in possession of a degree. Let us look at the successful electrical engineers of our day, and we shall find that the men holding the big positions are not often men of great academic attainments. I believe there are at least two reasons for this: first, because, with the exception of particular branches of work such as teaching, designing electrical machinery or in the applications of physical science and chemistry to industrial processes, no very great theoretical equipment is required, as, for instance, for constructing or running electrical plant or installing plant and wiring, etc.; and second, that for most of the latter positions the years between the ages of 18 and 22, if not spent in the works acquiring the extraordinarily valuable experience which only those years can give them by association with workmen and plant, are irretrievably lost. For this reason so many engineers with degrees fail to attain (or if they attain them at all have to wait many years before doing so) the positions to which their training would seem to entitle them. We should attach more importance to a record of achievement, with or without examination, than to examination qualifications alone; the qualities necessary for the passing of examinations are, by themselves, frequently of little use in business life, and by no means the most important. Let us not forget that a real engineer does not finish his education at an age when he leaves, or would usually leave, college. It will be within the knowledge of most engineers who are in middle life that at that age their real education had scarcely begun. Among the best qualities of a real engineer I should count enthusiasm in his work and profession. With enthusiasm, whatever the deficiencies of his training, he will go far; without it he cannot progress much. It should be our duty to create such enthusiasm; to destroy it should be unpardonable, and I was interested to find on my visit to America last year how much thought and prominence is given to this question, one of the reasons, I am certain, of the unexampled prosperity of their electrical and other industries at the present time. Another important quality of the engineer is imagination, the ability to visualize a design, a piece of work, a new device, the probable result of a certain line of action, etc., before it is entered upon. This quality is in a large degree an inborn gift, but it can be cultivated and should receive more attention in our educational system as it is not merely of value to the engineer alone. Its wider diffusion among the masses would make impossible such things, for example, as strikes of munition workers during the recent war, whilst to the engineer it is the basis of all sound initiative. As to engineers engaging in public life, where time and inclination permit of this we should not shirk this duty any more than any others where we can be of use to the community. Probably one of the reasons why more has not been done is that our comparatively young profession, with its tremendous rate of progress, can, and does, absorb all and even more (were it possible) of the energies of its members, leaving little time for work, which to busy men must often seem deplorably unfruitful. I am not sure either that the qualities of the engineer as an individual are so much superior to those of other professions in dealing with public affairs. Many of them are so much more capable in their understanding of the laws of Nature than of the laws of men and of the mind that, unless specially fitted for this work, they can only excel in questions for which their special training entitles them to speak with authority. That is not to say that they would not serve quite as well as, if not better than, many who now unfortunately deal with our public affairs.

Mr. P. F. Allan: For breadth and scope, insight and lucid analysis, the paper must be difficult to parallel, but for study I should especially commend the second part of Section (5), dealing with human problems and economics, and the first part of Section (6), dealing with the engineer in public life. Those parts in Section (3) dealing with the boy—and should we not now include "girl"?—who is to become an engineer, and that part of Section (4) which discusses the necessity for early contact with skilled craftsmen, are of great importance and merit our earnest consideration, even if we do not agree with all the author's conclusions. Difficult as it is to criticize, there is one point on which I should like a more definite pronouncement from the author, because I infer that on this point he has failed to take his own advice to consider every problem on its merits without being influenced by the preconceived notions of others. In Section (4) there is a cryptic reference to the solving of the "perennial question of the engineer-salesman." It is therefore evident that the modern tendency to question the usefulness of this type of engineer has been working on the author's mind. Further, in his description of the various types of engineers who form the body of members of our Institution, I note with regret that he has omitted to mention the much-maligned individual to whom I have just referred. I trust that this is inadvertent but, as indicated before, I have an uneasy suspicion that the author has fallen into what threatens to be a common error. I wish to take this opportunity

of ensuring that the proper place of the engineer-salesman in the economic structure of our industry shall not be overlooked in a paper of such importance. Perhaps it is not correct to say that the importance of the engineer-salesman—or, as I prefer to call him, the sales engineer—is too often forgotten, but it is certainly too often misunderstood. There appears to be an idea that he is merely the medium through which orders, which must, in any case, be placed with some one or other manufacturer, are diverted to one channel or another, according to his personality or persuasiveness. Actually, however, he is the link between the manufacturer or supplier and the user. Through him, many technical problems of great importance are discussed in a way that cannot be equalled by correspondence, and to his wide technical knowledge, insight and energy, must be placed the credit of very many of the improvements in the design and application of the plant in which we are all interested. It is within my personal knowledge that some of the most marked improvements in the design and construction of modern plant which have been made during the last two decades have owed their origin to the knowledge of working conditions and practical technical abilities of the sales engineer. The mathematical equipment of some of these men may not always be of the same high order, and so well kept up, as that of their brother engineers in works, designing offices, etc., although this is by no means an invariable rule, but it is always severely practical and is often of immense value to those whom they serve, who are not only their employers but also their fellow employees and the community at large.

Mr. W. G. Guns: It has been said that the greatest study for man is man, and the author has brought this subject before us in an interesting way in speaking of engineers. It has been said that a minister sees a man at his best, a solicitor sees him at his worst, and a doctor as he really is. How does an engineer see a man? Surely in the light of what he can get him to do, what use he can make of him, not for selfish ends, but for useful ends. An engineer's whole training is for construction, and not destruction—destruction of any sort goes against the grain. It is by exercising their constructive policy that engineers can be of service to the community.

Mr. A. H. Marshall: I should like to lay more stress than the author has done upon what is due to the engineer, as from my experience the engineer compares very favourably with people in other walks of life, both in his ability and in the discharge of his duty. What is wrong is that his activities are too much limited by financial and economic considerations and his status is not sufficiently well defined; whilst he does not get the public appreciation that more assurance of his own importance would command. One always feels that the engineering profession suffers by comparison with the medical and legal professions in that it has not the traditions and privileges of these older bodies. In this respect probably nothing has done more than the registration of the individual member and I could have wished that the author had said something more on this aspect of the matter. It is to such papers as his that one looks for the development of ways and means to give the engineer a better position in society, and I hope that the outcome of this discussion will be the setting up of a defined course of training with engineering degrees and the creation of a statutory body to register ability and character. These would do much to stimulate the moral qualities which, as the author so ably points out, are the basis of a successful life.

Mr. J. Gibbins: We get many scientific papers during the course of a session, some very highly technical, and we are not all so clever as to follow them and discuss them, but I venture to suggest that such papers as the present one would prove very popular. The educational value of the paper is tremendous, and those of us who are fathers will do well to digest it thoroughly.

Mr. H. Bridges (*communicated*): This paper should be read in conjunction with Mr. Maccall's Address to this Centre, and the Training of Engineers Scheme now being introduced by the National Joint Board of the electrical power supply industry. It is good sometimes to get away from the mathematical problems and technicalities of everyday experience and consider for a time the human side of life. To have our attention drawn to the fact that we are something more than mechanical instruments, that we are human and divine, that there is that part of our being which requires nourishment as well as the physical, is certainly most stimulating. The author has reminded us that we are soul as well as body and, after all, it is the soul which makes the man. There is very little, if any, room to-day for the soulless man. It is good to get beneath the thin veneer and get to the heart of things, and the author is to be congratulated on bringing this important factor to our notice. Throughout the paper, importance is laid upon seeing that the right man gets into the right place, and this would appear to be the aim of the author. Whether he will succeed in establishing the right formula remains to be seen, but I certainly think and believe that he has taken the right course. The author also emphasizes the fact that many become engineers who would have succeeded better in another sphere, and vice versa. In consequence, the whole world suffers and progress is somewhat retarded. After all, considering the rate of progress in engineering as outlined in the paper, there must have been a great many round pegs in round holes and square pegs in square holes, or otherwise such progress would not have been accomplished. The author has also laid stress upon the importance of the method of training and seeing that those who get through are "real engineers." To secure this end, the author states that "more value would come to be placed upon achievement than on examination results." The tendency to-day is inclined towards the latter rather than the former. It would be interesting if the author would enlarge upon this aspect of the position, seeing that achievement has in the past had more or less equal consideration with examination; the future, however, will make equal demands upon both, and the engineer who shows equal ability will no doubt be in first demand. The author states that "the finding

of engineers" (and I take it he means "real" engineers) "is more important than the method of training." That may be so, but he does not state how one is to be sure "he is a hare"—he may be a rabbit, but may make just as good soup after he is "cooked." Surely some method of training is essential before the "real" engineer can be found, and therefore the method of training appears to be the most important, so that one can at an early stage find one's "hare." The author appears to favour restricted supply, but this restriction should at least be limited, as the requirements of the future are unknown. Also, by being too strict at the beginning, many who would otherwise have made "real" engineers may be excluded; unless, as the author hopes, the teaching profession may, by careful study to this end, be able to establish some formula which would give some indication of a positive nature to guide pupils as to what profession they are most fitted for. The author quotes Dr. Johnston as saying, apparently with regret, that "there are no records kept in public offices of the state of supply and demand in the various professions." It may be of interest to state that the Training of Engineers Scheme previously mentioned provides for a register of qualified engineers for the electric supply industry, so that it may be possible for youths to find out if it is worth their while entering this section of engineering. This register should prove of great value to all concerned. Some are born engineers and are quickly discovered, some are not, but the fulfilment of that purpose is destroyed in a multitude of instances by the adverse influences which attack the life in its early stages; the life is weakened at its start and, unfortunately, the new life never finds its real purpose except by determined effort on the part of the individual in after-life—hence the world is all the poorer. It is gratifying to know that gradually, but surely, an improvement is being established and many causes of stumbling are being removed so that the mind of the future generation will become clearer and more powerful and the whole universe will benefit extensively. We hear a good deal to-day about industrial problems, and the question is often asked: "What is wrong with industry?" There is nothing wrong with industry—it is the soul of man that is wrong and requires righting. Most people look at things from a selfish standpoint and wonder how they will profit, but, after all, the man who wraps himself up in himself makes a very small parcel. Industrial trouble is caused by the employer and employed failing to realize their duty in life. One asks for a reduction of wages and the other a reduction of profits, whereas both are wrong. We should centre our thought on increase, not reduction. It is a change of outlook that is required, the employer interesting himself in his employee and the employee interesting himself in his employer. Everyone, from the office boy to the manager, has his duty to perform and, if either neglects it, the whole concern suffers. He that hath much, much is expected of him. The author states that "the mechanism of the world rattles and rumbles as it works" and asks the question, "cannot those who make it discover a lubricant for it?" The lubricant is mentioned in the first paragraph, namely, "the exceeding of mere duty." In other words, quoting from the Scriptures, "if a man compel thee to go one mile, go with him twain"—obey the law and give something over. Duty only takes us one mile, love and sacrifice take us to the second. It is the overflow of our service that counts and acts as the lubricant. Most of us can manage the one-mile limit; it is not really difficult, but it is a poor type of life. To go the second mile costs us something; therein lies its value, it means a struggle to do the extra, but that is the test, there lies the opportunity. The man who takes a long view of life to-day is often depressed, there is something in the future which gives a feeling of fear, strange stirrings of the coming storm. The time has surely come whan all men, in spite of party, creed or class, should begin to practise a little generosity in their dealings with one another. So soon as we all begin to tread the second mile, so soon will things change. This may be described as sentimentality, but surely there is room for the exercise of love and sacrifice, even in the commercial relationship of men. Has not the application of the principle of "exceeding mere duty" been the spirit of all pioneers to whose efforts we owe so much to-day? I venture to say that the application of this principle is the only safe and permanent solution to the industrial problems of the present day. It may be said that this is idealism. It may be asked: "Where, or when, has this sort of thing been tried, when was it accepted as a principle between individuals or classes or nations"? When? Where? The answer may be, "Never." Then why not try it now? The world is stuck at the first mile at mere duty, which is irksome. I venture to predict that if this principle was adopted by all there would be no question as to the engineer's due—he would get it. May this paper be the means of awaking in the minds of all engineers a new zeal, calling to them all over the world to realize their duty in life (and duty includes seeing that the engineer receives his due) and to show the way to the second mile and, quoting the author, "putting into the making of the web every bit of us." When we have done that, and not until then, shall we be sure of finding the right man for the right job and so providing the lubricant which will make all industrial machinery run smoothly.

Mr. J. Dickinson (*communicated*): With regard to the subject of examinations, I should like to point out that at Armstrong College, in the electrical engineering department, the students' performance and aptitudes are observed continually by their teachers, who are also examiners, and notes are made on each individual. These observations all play a very important part in the examinations which the students take. So it is clear that an arbitrary set of questions, answered during a fixed time, does not by any means provide the only criterion of the students' fitness for receiving a degree in electrical engineering. They are carefully studied during the whole time appointed for the degree course, which may be either 3 or 4 years. There is no doubt that examination tests are themselves unsatisfactory, but I wish to show that judg-

ment is formed on sustained performance. However, the most important period for sifting students into their proper vocations is during school training before they are admitted to the university. Another point to which I should like briefly to refer is the subjects of economics and finance. Engineers generally do not give these subjects the attention which they require. They feel, perhaps, that such things are highly specialist in nature, and fear to express opinion or even to study the facts, doubting their own competence to deal with them. Yet these facts must be faced, especially when there is even the possibility of the author suggesting "whether it would have been better to scrap all our war surplus . . . and thus to keep some men . . . working." This is a dangerous and sorry plight. I should like to suggest a line upon which, in my opinion, careful thought might be directed with advantage. What is the primary function of industry at the present time? Is it the provision of goods and services essential to the well-being of the State, or is this merely subordinate to the more immediate purpose of operating upon money in order to increase that money? In other words, are goods and services just a means to profit? It seems that this is so, and, consequently, any new scientific device which produces the same goods and services at a cheaper rate than those devices already in use, is beneficial to this end. However, directly opposed to this is the necessity of providing adequate work for the majority of individuals in the State in order that they may earn sufficient money to meet their immediate needs. Can these two sets of apparently conflicting conditions be reconciled ultimately without modifying the principles governing industry to-day? Wealth does not consist in a static quantity of things possessed, but in the potential capacity of producing goods and services. In other words, if Q be quantity, then current-flow is dQ/dt, or the rate of change of Q, and this latter condition is, strictly speaking, analogous to wealth. Under such conditions money would be the means, goods and services would be the real aim or end of industry, and unemployment a much less difficult problem.

Mr. G. N. Peel (*communicated*): After speaking of the value of intelligence tests, the author proceeds to say: "Further, a boy's personality will develop finely under treatment like this . . . he will climb . . . high in thought. . . ." I take it that the actual results of the intelligence tests are to be made known to the students; but this hardly seems to be a desirable course, because, under the influence of his "intelligence quotient," the clever boy might tend to become an intellectual prig, whilst the less-gifted boy might receive a mental snub which would spoil his future outlook and ambition in life.

[The author's reply to this discussion will be found on page 229.]

NORTH MIDLAND CENTRE, AT LEEDS, 24 NOVEMBER, 1925.

Mr. S. D. Jones: The majority of boys want to be electrical engineers. Parents have come to me and told me that their boys are sure to make good engineers, as they have put up, say, electric bells. I have asked the parents if they have observed their boys as regards their bent, and I find that they are amazingly ignorant of the characteristics of their own boys. They really seem to be the very last people to decide what their boys should become. This also applies, I think, to schoolmasters. I recall the case of a schoolmaster, a very able man, who sent to me a lad who wanted to be an engineer. He was a very clever lad, but I had not been speaking to him many minutes before I came to the conclusion that there was nothing in his disposition to warrant his entry into the engineering profession. I am very glad that in his case his parents thought the matter over, and the lad is now going in for another occupation. At the same time the author is evidently thinking of the boys who are pre-eminently fitted to become engineers. In the main I agree with Dr. Steinmetz that "The scientific fact is that people are made out of the right stuff, but our problem is to find a way to release their creative energies." After all, most men, women, boys and girls going through life have to fight; they have to overcome their difficulties. I believe that the average lad, in whatever walk of life he goes, must experience a great deal of drudgery and difficulty, and, after all, the first thing is to cultivate personality by the boy's strength of character and his readiness to face life. I have had some boys working under me since I have been an engineer, quite ordinary boys, who have gone out into the world and made good. Some of those boys have gone to America and other places; they have fought their way through. At the same time there is not the slightest doubt that a great deal can be done in finding out what boys should become. It is no use putting a boy entirely musical, or with an artistic disposition, into the engineering profession. I think that all engineers should study economics. A year or two ago I saw about a hundred new locomotives lying useless on the banks of the river Dee. They were locomotives that were built during the war. For some strange reason—uneconomic, I think—those engines are still lying there, because it is felt that if they were put on the market they would enter into competition with engineering firms who build locomotives. That seems to me an utterly foolish way of looking at the matter so far as economics are concerned. Surely the locomotive works, which would have been deprived of work if those engines were put into commission, ought to have diverted their energies to some other work. It is not so long ago that first-class newspapers would have considered it a matter good for trade if a fire took place, or if windows were broken. It is not good for trade. Waste of any kind is a terrible loss, but the same economic fallacies still largely obtain. How is it that engineers with their great brain power—for, after all, engineers have done a great work in the world—do not take a greater part in public life? The only reason that I can think of is that engineers are more in contact with material things, whereas men of affairs come into contact with persons, and in doing so see many points of view. If engineers

were to become members of borough councils and of Parliament their minds would be broadened; and they would have a tremendous influence on public things and public life.

Mr. W. E. French: Before we start to discuss how to find the engineer, which appears to be the kernel of this paper, it is necessary to be quite clear what an engineer is and what constitutes his qualifications and his duties. The old adage, that an engineer is a man who produces for a penny what most people can produce for a shilling, provides a crude, but singularly apt, definition. It implies a fine scientific training which gives him a clear conception of the forces of Nature, and a sound knowledge of the materials she places at his disposal. It implies the ability to use them to the greatest possible advantage, and to apply them usefully. Ultimately, it implies that he must possess keen financial instincts and great business acumen; to this add faith and courage, indomitable perseverance, imagination tempered by clear thinking—in short personality—and we have the perfect engineer, the "head and shoulders" above the average kind, and the leader in his profession. This type of engineer who combines the scientific mind with talent for application and financial ability is indeed rare; so we are immediately driven to compromise and to discover who is likely to excel in any one of the branches to be enumerated. This already leads to partial specialization, because we have to find and train men whose bias may be either scientific, or may lie in application, or may be towards finance and engineering economics. At this point I should like to state in a general way what appear to me to be the duties of an engineer, and how they may be classified:—

The Research Engineer.—His inclination and abilities belong to the provinces of pure and applied science, and his realm is, to use the author's metaphor, the tiny empty space between the nucleus and the electron. The sphere of his activity is the research departments of the great engineering and manufacturing concerns. His training will be entirely the charge of the science and technological departments of the universities.

The Design Engineer.—His abilities are still highly scientific, and his mathematical equipment must be good; but above this he must also possess a high capacity for application. His field is the design of machinery, bridges, ships; the design of switchgear and protective devices used in electric power systems, and the apparatus for radio telegraphy and telephony. His education and training is the conjoint responsibility of the universities and the engineering works. The next class is not so easy of definition, and I shall designate the engineer who belongs to this class as the *organizing and projecting engineer.* My meaning will become clearer if I enumerate what I believe to be his activities. He is the man who plans and directs our electric power supply, irrigation, water supply and the sanitation of large cities; the man who is responsible for our communications, whether they be the railway, the telegraph or telephone services. His education should have a definite practical tendency, and the major part of his training should be received in manufacturing works, electricity supply work and other civil undertakings. His technology may be received at a university, but I think he will be equally well served by our senior technical colleges and senior technical schools.

The Works Engineer.—He is familiar to us as the works manager. He may have been classified under the title of organizing engineer, but his work is so intensely specialized towards shop and works practice that he becomes in this respect a type of his own. He must have served a full apprenticeship, preferably in large and modern works, and he need only gather such knowledge at senior technical schools as will enable him to appreciate the scientific facts placed before him in designs and drawings, his business being to put them into material form with sound workmanship, at the lowest cost and with the greatest speed. He is essentially an individual with an accurate knowledge of men, materials and methods.

Finally, there is the *sales engineer,* or the "*engineer salesman,*" possibly better described as the "commercial engineer"; although none of these appellations correctly describes the case. The highest type of commercial engineer must be a man of great and universal ability. He must be a diplomatist, a first-class debater and psychologist: Having to meet the leaders of industry and of the engineering profession, his technical qualifications must be of a high order; the designs and technical policy of his firm must be at his finger-tips. In addition, he must be well up in political economy and international politics. From the rank of the commercial engineer will be drawn the general manager and the managing engineer, and what the author describes as the public organizer of our engineering resources. The sales engineer of the past just happened; the commercial engineer of the future will have to be carefully educated and trained. He is undoubtedly a university man; not only for the sake of his technology but because the universities will also equip him through their social and corporate activities with the qualifications so needful to his career. The stepping-stones in the practical career of both the commercial and the designing engineer are the post-graduating courses arranged by the large manufacturing firms.

Having arrived at some definition, however incomplete, of the engineer and his activities, we can now proceed to the author's process of "finding" him. Here I am not inclined to agree with the author that we must find the "head and shoulders" above the average man. Cream always rises to the top, and he will find himself. It is rather the good average man we have to discover, and allot to him that sphere of engineering most suited to his inclinations and ability. In this respect the author's proposal is a good one, with these additions: that the sifting process of suitable youths from early school days should not be confined to the schools, but should be continued in the universities, and finally to their practical and business lives. There is not much advantage in recording a boy's school performance or a young man's university attainments if the final results of his after-life remain unrecorded and obscure; then no judgment is possible, and advice as to a boy's future would be uncertain and lack definite value. I do not foresee any real difficulty in devising machinery to produce such records and statistics. Where I foresee real difficulties is in obtaining reliable statistics when a

man has completed his school or university training. I find it very difficult to keep in touch with past students. If the launching of such a "sifting" scheme were contemplated, this is the point which should receive serious attention, and if the work is to be of any value at all the hearty co-operation of employers must be assured. Many of the large electrical manufacturing firms have elaborated a system of records for their apprentices and post-graduate students with a view to advising them as to their suitability at the end of their courses for any of the branches of electrical and mechanical engineering. It will thus be seen that the electrical industries have already made an important step in the direction the author has indicated.

Mr. O. C. Dinerman: The author's "lethal chamber" is rather a drastic procedure to adopt when dealing with men who, owing to certain conditions surrounding them in their early days and adolescence, such as environment, health, etc., have not been able to reach his standard of citizenship. There are many men and women who, by some selective natural process, cannot exercise their individualism to the full, frequently owing to a matter of ancestry. Bunyan, seeing a manacled man, said to his friend, "There, but by the grace of God, walks John Bunyan." I think we should be more lenient to those men and women who fail to realize their duties in life and give full service, and endeavour to understand the reason of their shortcomings and, understanding, to forgive. "To understand all is to forgive all." Thus may some of us help to steer them into their proper channel in life. Our aim should be to bring up the average into a high state of efficiency. Dealing with the finding of engineers, the author's method of selection has many drawbacks. The whole matter of occupation must, in the very nature of things, be plastic. One can safely say that, in the main, engineers are not born, they are made. It is a quite different calling from that of a painter or poet; it is a mechanical art and, as such, can be acquired to a high pitch of perfection. A boy may have a strong penchant for engineering up to a certain age, and suddenly drop it; on the other hand, he may follow that bent and be a mild success. Rather let selection be free, but once having taken it up then is the time to concentrate upon it and endeavour, by sheer hard work and enthusiasm, to make a success of it. It is the singleness of purpose in any mechanical art that makes for success. Some there are who are born engineers. Nature breeds a genius now and again, and then breaks the mould. We must not forget that many successful engineers began life in other professions and trades, and achieved fame for their administrative powers, inventiveness, etc. In regard to the sales engineer, there are many qualities that go to make him up. I should say that adaptability, service (and lots of it), energy, self-reliance, good judgment, enthusiasm and cheerfulness are enough to make any one successful. Two or three of these would suffice. The sales engineer should also be able to sense the requirements of the district he works in and duly report. He should be able sometimes to give broad hints to his works in such matters as design, advertising, etc., and always think of himself as part of the organization and working with it. He should not bore his customers, and should avoid the sin of limitation. Enthusiasm is a quality which, being of the spirit, engulfs most others. It is amazing how enthusiasm put into a relatively dull occupation enables us to see some latent pleasure in it. But most of us are in congenial occupations which should give us scope for the exhibition and development of our true selves, and however hard the work is, it will afford us the highest pleasure. All work done well produces a feeling akin to joy. We can express our creative spirit no matter in what sphere. The service of our fellow members should be the chief goal. The humble worker becomes a mighty craftsman when his soul speaks through his labour. That is the acid test of character. Amid the constant flux of things, honest work is the one finally enduring, and if there is no other immortality there is one along the line of our daily duties. Apart from the great masters, let me give an illustration: A village craftsman, a worker in wood or clay, dead for centuries, his grave flattened as the surrounding land, perhaps built upon, yet behold his work lives after him, his tables, his chairs, clocks and pottery, a sensuous feast for the eye, a symphony in graceful curves. At the time a simple village worker, now nameless. His creative spirit found expression through his craft; his the achievement, ours the harvest. Play the game for its own sake, and let the prize go to anyone who may desire it. Our own work in industry should be played and won on points, and, at the end, show not only the material result which is the prize of victory, but a team happier and more prosperous than others. That is the game of industry and no unworthy game for men to play. Strive for the common good, for the glory of achievement, and the material reward must come as a *sine qua non*; whether success or failure comes at last, the effort brings the reward. For the successful and happy man is he who serves best, who is great by being humble, who believes all things, hopes all things, and endures all things, not that others may love him, but rather that he may learn to love them.

> "Man hath his daily work of body or mind
> Appointed, which declares his dignity
> And the regard of Heaven on all his ways,
> While other animals inactive range."
>
> MILTON, *Paradise Lost.*

Colonel H. C. Fraser: The supply and training of young men for the electrical industry are on a higher level to-day than they have ever been. Candidates are better trained at the universities and in the workshops, and are turned out more capable of competing with modern conditions than has been the case previously, and I think that a survey of the younger members of the personnel of industry to-day gives one the greatest hope for the future. On the question of the selection of engineers, the author goes right back to the rights and duties of life and the rise in modern engineering. Dealing with the selection of suitable boys for the profession, be it engineering or any other, the first and most important point to my mind is the training which a boy receives in his home. After all, a boy goes through the hands of his mother to start with and then it is that the foundation of his powers of observation and imagina-

tion, which are all-important to him in after-life, are first taught, and I believe that the credit is due to the mother rather than to the father. The boy then goes to school where he is generally further developed and learns to play the game and eventually passes on to the university, and his period of university training is, as Mr. French said, the time when he gets an idea of creative action. He is brought into touch with a corporate body with all its activities and deems himself of some account in the world. There is, however, a modern tendency to lay too much stress on the university training and not enough on workshop training. The ideal, I think, is a sound university training, but without a knowledge of the working man he will be lost in after-life and will lack that knowledge which cannot be obtained on a slide rule. My remarks have been confined more especially to the upbringing of engineers, as I consider that is the most important part of their lives.

Mr. W. H. Wraith: The engineer's view of life concerns us all from the highest to the lowest. If he does his duty he is benefiting the whole community.

Mr. W. F. Cooper: When I went to school my tendencies were not towards engineering, as I was on the literary side of the school. In such subjects as mathematics and chemistry I occupied one of the lowest positions at the end of the term. On the other hand, I was always interested in engineering and, as a result, have taken it up as a career. I have not regretted this. I think that to a great extent I have made up for the lack of mathematical knowledge that I showed at school. This lack was a hindrance to me, especially at the university.

Mr. J. W. J. Townley: The author has rather narrowed down his proposals for the selection of the engineer, but I think it will be agreed that no great achievement can be carried out by one type of individual alone. Great results are obtained by the co-operation of very different types of mind, and in no profession is this more marked than in our own. There is the man who is specially adapted for scientific research; he is capable of producing certain results but in many cases not capable of applying them. These results, however, are usually applied by another and more practically-minded type, whose duty in life appears to be making use of the tools put into his hand by the research man. A very necessary type, too, is the engineer with literary abilities, of which we have a very good example in the author of this paper, and I think we are very short of that type of man in the engineering profession, with the result that the value of our work is not always recognized, because it is not often adequately described. I would suggest, therefore, that it is not entirely a good thing to be too restricted in the selection of boys to train as engineers, provided always that they have some liking for engineering matters. The author refers to the desirability of the engineer taking his part in public life, and this unfortunately the engineer very rarely does, and thus, when a commission or committee is set up to inquire into any problem it consists usually of lawyers and business men, who call the engineer in as an expert adviser or witness. There is no particular reason why the engineering profession should not be well represented on such committees or commissions, and I am sure, knowing the type of men we have in the engineering profession, they would contribute something to the solution of some of our large national problems.

Mr. R. A. S. Thwaites: At the top of page 199 the author says: ". . . the essential importance of never doing a thing ourselves if we can find someone else to do it well for us." At first sight that seems to be a direct incentive to sheer laziness, but rightly applied I think that is the essence of successful organization. Most of us know men—clever men, perhaps brilliant men—who try to make a one-man job of work which should be really tackled by an organization, and I think that this when rightly worked out is really the foundation of some of those very large organizations that have been built up by, say, the late Lord Leverhulme, and other similar heads of industry. There is an old saying that the man at the top should never be busy—in other words, he should have time for coping with emergencies, studying conditions, and organizing those who serve under him.

Mr. M. Wadeson: The "common good" is mentioned in the paper in many places. One of the first things to do is to decide what is the common good. What may be the "common good" in one era may not be in another. It may be that the index of the sum of knowledge at the present time will only be the index of the sum of ignorance in the future. On the question of selection of the engineer, the author says that we must observe the nature of children at an early age. In my opinion that is nearly impossible. It is only in exceptional cases that any reliable indication of predilection in a particular child will show itself at an early age. Further on in the paper the author speaks of the "head-and-shoulders-above-his-fellows" man. I take it he means a genius. Genius has been defined as "an infinite capacity for taking pains." Throughout the paper the author advocates taking pains in whatever is done. This capacity for taking pains is a trait which can be developed in anybody, and since engineers are, after all, ordinary people, they are not necessarily all geniuses. The "head and shoulders" people would do quite as well in any other walk of life to which they were called as in engineering. The author mentions that some boys have no liking for one thing but that they show a distinct liking for another. I think it is inherent in young people nearly always to show a liking for what one might call manual work, but it does not follow that when they get to more mature years their likings will not be changed to a very great extent. The engineer is an ordinary person with a specialized training. The ordinary training or the opportunity for the ordinary training should be given to everybody, and the specialized training should be undertaken at a later date when the career definitely settled on was that of an engineer. On page 199 the author says: "Engineers have gone on inventing, often enough not realizing that the results of their work might be used for merely commercial ends." I take it that if any invention has a commercial value then it must be considered that the community as a whole wish for it, and therefore I cannot see what his objection is to an invention having a commercial value.

Mr. H. Moss: When I first saw the subject of the paper I thought that the author was going to deal with

the matter on an entirely different basis, in fact I thought that he was going to deal with it from the practical point of view. I think that we, as a body of engineers, know to a great extent what our duties are in life, but we do not get our honest dues. The whole paper bristles with what may be termed social-reform matters which cannot be discussed in a limited time. The author says on page 198 that an engineer should study everything connected with the running of this life. If he were to do this, however, he would have no time for his business. I am quite in agreement with the view that the engineering industry of this country ought to have more representatives on our governing councils. When I say "governing councils" I refer to municipal bodies and Parliament, because I feel there are many capable men in our ranks who would be a very valuable addition to these bodies.

Mr. H. W. Walker: In regard to the training of an engineer, and particularly the selection of an engineer, a little anecdote that I heard some time ago may be of interest. The parents of a boy, probably about 12 to 14 years of age, intended him to become an engineer. Mathematical problems worried him very much, and someone who was visiting the house drew his attention to the fact that he must persevere and do all he could to train himself in mathematics and become a good engineer. "Well," said the boy, "if engineers have to bother with that sort of thing I would rather leave it alone and be an engineer like father." This remark of the boy indicates how careful parents need to be in selecting a suitable profession for their children. The paper opens up a line of thought which I hope will be further developed, as such developments would be a great blessing to the rising generation, and prevent so many square pegs being forced into round holes.

Mr. T. H. Seaton: A previous speaker has dilated on the advantages of a university training for the engineer, but in my opinion there is something wrong with the present system of university training. It is often looked upon as being an end in itself, whereas it is really only a means to an end. If a boy is destined to be an engineer it is best that he should start his practical training either on works or in the shops as soon as possible. At 16 or thereabouts he will find that the men will take an interest in him and teach him willingly. He will learn something of their lives, difficulties and aspirations, and the knowledge thus gained by personal contact will be of inestimable value to him in after-life if he has to control men. A man who has been to the university comes on to the works or into the shops when he is practically a man and rarely seems to pierce the natural reserve of the workmen. Personally, I took advantage of the technical courses of a university during my practical training, and found that an excellent method of obtaining the most value from the theoretical side. This is the day of great amalgamations and there is a danger of their failing by neglect of the personal equation. Men are put into positions of authority, labelled, and submerged by a flood of forms, statistics and returns, often rarely coming in contact with the men they control. The workman feels the loss of that personal contact with his chief, and that in many cases the latter does not understand his point of view. I feel sure that if we could get more of the personal element into industry and recover the confidence of the men, many of the industrial troubles of the present day would rapidly disappear.

[The author's reply to this discussion will be found on page 229.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 1 DECEMBER, 1925.

Mr. J. Frith: I propose to say a little about the selection and training of the young engineer. It is gratifying to feel that our parents and guardians took such trouble over finding out that we really had the root of the matter in us. I wish that more schoolmasters were like the author's friend and tried to help the boy's parents to start him in the right calling. Too many boys have been made engineers because they took the kitchen clock to pieces. Mathematics or physics is the sure foundation to build upon. I say "or" because the two are *very* rarely found in the highest degree in one individual. They are not attainments so much as types of mind. If the boy shows any signs of being able to profit by it, by all means let him go to college, and, I think, straight from school. For, although I see to the full the arguments in favour of some works experience first, I think that continuity is of even more importance. Continuity of the habit of brain working, especially in the evenings, and, perhaps more important still, the continuity of works when he does get there. My advice to the college is: Don't spend many valuable hours in trying to teach the boy what he will pick up in much less time in the works, but teach him what he may never again have the opportunity to learn, the broad principles underlying the nature of things and not merely of the things which are to bring him bread and butter. The popular idea of the college-trained youths swaggering into the works and proceeding to teach the staff how the works should be run and, furthermore, demanding a large salary for doing it, has very little foundation in fact, but is largely a bogy set up to be knocked down amid the cheers of the "practical man." My experience is more that the college student approaches the works with a very real humility and is very willing to begin at the bottom of the ladder; but that having been to college he will be both quicker in the uptake and will see further round a problem than the man who has been trained entirely in the works. I should like to say a word of encouragement to the engineer who wants to get out of the rut and try new ways of doing things. I know only too well that all the inducements are in the other direction. Get off the beaten track ever so little and difficulties spring up. It is so much easier to do things in the old, tried way and to play for safety, than to be original. If the pioneers had done this where should we be? The motor-car trade and, more forcibly, the war have taught us that there may be many other ways of attaining

the desired end than those prescribed by orthodox engineering.

Mr. B. Mouat Jones: Professional bodies, it seems to me, normally talk a great deal, and quite rightly, about their work and its result, without paying much attention to the relationship of that work to the general scheme of things. In my opinion it is desirable that at comparatively rare intervals they should have a sort of mental stocktaking and put questions to themselves as the author has done. This applies to all professional bodies. I agree with practically everything the author has said; but favourable criticism does not, as a rule, add to the vigour of a discussion, and I have therefore endeavoured to find one or two points on which I do not quite see eye to eye with him, although I do not think there is any serious difference between us. What I have to say is really by way of amplification. Under the heading of "The Finding of Engineers" he says, "It is the head-and-shoulders-higher-than-their-fellows people whom we want specially to discover." I am inclined to think that is not quite so. Those people are the people who discover themselves; they do not want so much help as the average person who is not going to be a leader or a first-class man. I also disagree with the statement on page 195: "Strictness at the beginning may reduce the number of those who become engineers; but that is what is needed." I think that engineering training is, in itself, as good a training as any for the purpose of performing the functions of good citizenship, and is a better training than most. I believe that the more men we have who are trained as engineers the better, whether they finally become engineers or not. I sometimes put it to my students that merely because they have had an engineering training, it does not follow that the only thing they can do is engineering, that a man who goes to Oxford or Cambridge, say, and learns all about philosophy, history, Latin or Greek, considers he is fully capable of doing anything and does it very well; but I am certain that a person trained as an engineer could do it just as well and possibly better. That is why I like to say sometimes that I feel the more trained engineers we have the better, even if they do not necessarily become engineers, or even if they do not happen to be engineers of first-rate ability. If they get into other walks of life it is a very good thing for those other walks. To limit artificially the number of those who are going to be engineers seems to me a very dangerous thing to do. The economic situation is likely to do it automatically. The supply and demand in regard to engineers will always be roughly in consonance, although there will always be a small lag, according as the demand increases or decreases. I suggest it would be a fatal blunder to limit the number of engineers by any process of merely selecting those who are going to be first-class men. There will always be a great need for the rank and file of good average engineers of second- and third-rate ability. The author enjoins upon us the necessity for recognizing the "essential importance of never doing a thing ourselves if we can find someone else to do it well for us." That is very important. But if all engineers are leaders and first-class men, the first-class men will have to do second- and third-class work and will cease to do first-class work. I want to put in a plea for the finding, utilizing and training of the second- and third-class men, and not to lay too much stress upon the finding of the first-class men, who, I think, will normally find themselves. In connection with the discovery of future engineers while still of tender years, the author says on page 195, "In pursuit of our aim we must discover the inmost nature of children at an early age." That rather scares me, as it suggests that we should apply intelligence tests and psycho-analyses to these young children. What he really means is that the headmaster should be in a position to say which boys are suitable for certain professions. That is useful so far as it goes, but it is also very dangerous, particularly in this way. To begin with, the percentage of boys who show any particular bias in any direction up to the time they leave school is remarkably small. A very great proportion do not show any particular bias. They are by definition the average boys, and I rather fear that anything done to determine a career on the lines suggested by the author and Dr. Johnston might lead to the neglect of the average boy and to difficulties with the brilliant one. It must not be forgotten that a boy at school who may show a very great aptitude in a particular direction often turns out, in later life, to be a duffer in that direction, and vice versa. The ordinary boy often turns out to be much better than the brilliant fellow at school. Dr. Johnston has said some rather curious things as to his method of choosing the careers of boys. In choosing a boy for engineering he wants the boy who can inspect a structure and tell instinctively what parts are in a state of tension or pressure, and what must be done to ensure stability. I do not think any man can do that. He may think it is done by instinct, but his instinct is the result of long training and experience, and if I felt that engineers were going to build bridges by instinct, and locomotives in the light of faith, I should take to walking. A boy who can do that sort of thing by instinct is a freak or a victim of over-specialization, and has lost a great deal of the other things he ought to have been doing. I think that we run a great danger of over-specialization if we adopt such means as those for deciding what careers boys should follow. When a boy is found who shows a particular aptitude in some direction do not discourage him, but do not encourage him too much in that direction, because it may not in the long run be the thing for which he is really fitted. Another point to remember is that a very large number of people who become engineers cease to be technical people and become more or less administrators. To judge from statistics taken from the College of Technology and the Leeds University, between 50 and 60 per cent of engineering students who go into industry become administrators. In those positions technical knowledge is a very desirable and useful asset, but they want a very great deal more. They want those things which we shall not necessarily get by selecting boys who can inspect a building by instinct. In conclusion, I am in entire agreement with Mr. Frith's remarks on college training.

Prof. Miles Walker: Believing that the true life is the life of service, I am afraid that our day schools do not bring that point sufficiently before the boys. They are also deficient in general training in ethics;

it is left too much to home influence, and the mind of the boy is not turned to those important ethical principles which are really at the basis of good society. In my school-days, when the question of a suitable profession was discussed, the point usually stressed was, how much can be earned? How far any particular profession was of use to the community was hardly discussed at all. This matter is not one to be talked over in a pious way; we must make a definite attempt to bring into the education of all young people the fact that the future of civilization really turns upon bringing them up to believe that they must give rather than get. The mind of the young child is so supple that it will turn one way or the other, and we can see in many actions of children that they are just as delighted with doing something to please somebody else as they are to get something for themselves. If they get on the wrong track it is simply because the general tendency of education as a whole is in the wrong direction. The question of service to the community is particularly important to the engineer, because the monetary remuneration he obtains is, as we all know, altogether inadequate when we consider his long training and the amount of mental effort which he has to put into his work in order to achieve success. In discussing with a youth whether he should take up engineering as a profession, we can put the matter to him in a very much truer light if we remember that the service of humanity is, after all, the main object of his existence. I have in mind many cases, but I shall refer merely to two, and I sometimes narrate these two incidents to young men who are thinking about a profession. A young man succeeded his father in a grocer's shop. He did not even make the effort of starting the shop, but he was well-behaved and, I dare say, conducted the grocery business exceedingly well. In about ten years' time he was making £2 000 a year, was possessed of a very fine motor-car and house, and was a very respected citizen. About the same time, and at the same age, another young man took up engineering as a profession. He worked very hard to get an engineering degree, and afterwards went into a manufacturing concern. In a few years' time he was receiving about £350 a year, and after ten years about £750. He thought that he was doing well, and so he was from an engineer's point of view, for he held an important position in a big manufacturing concern. His friends regard him as a successful and clever engineer; but everyone will agree that his monetary remuneration is quite inadequate, although at the same time I must say most emphatically that the monetary remuneration is unimportant. Let these two men arrive at the age of 50 and look back upon their past life. The grocer is respected by all people, gets into nice society, and everything is going on well; but what has he to look back upon as his life? What has been his life? Now consider the engineer. When he is old he goes to the works and is respected by all those in it. He has designed machines which have been running for 20 years and have perhaps generated millions of units. How many thousands of homes has he helped to light? How much labour has been saved? That old man, I say, is the happier of the two.

Mr. A. P. M. Fleming: I am going to confine my remarks to the Section of the paper dealing with the finding of the engineer, which, after all, is only a mathematical equation. We have on one side the requirements of the job, and on the other the latent capabilities of the man. We have to balance the two. Those who are responsible for the training, such as Mr. Mouat Jones, have a comparatively easy job, but those of us who are occasionally meeting the products of the universities, the very raw material they turn out, have a fairly difficult job. The real problem is the other side of the question: What are the latent characteristics of the man? It does not matter whether we are dealing with a man who has been to the university or one who comes from an elementary school and climbs up; they both reach the same level if they are made of the right stuff. Whether we are dealing with first-, second- or third-class men, the real problem is to know what their real capabilities are, and I do not believe that we shall get very much help from the schoolmasters. It is not because they are unwilling or because their sympathy is not there. I had occasion lately to discuss this point with 10 leading schoolmasters from the elementary schools in this city, and when I began to probe them as to what they could do in regard to guiding youths I realized that, after all, engineering is only one of scores of vocations, professions or jobs within a $\frac{1}{4}$-mile radius of the school, so what chance has the schoolmaster of knowing, except in a very elementary way, the requirements of all those jobs? Here in Manchester we are in advance of most cities in trying to find a way to equate the capabilities of the very young people who leave school at 14, 15, or 16, for the jobs that are open to them. A very definite effort is being made, but it is entirely inadequate, and we must not expect too much from it. Neither do I think that there will be much help from intelligence tests and the work generally of the psychologists, although one appreciates the attempt to solve the problem on scientific lines. There is a need of some means for getting into contact with boys and girls at about 13 years of age and beginning, not to influence them in the choice of their future work, but to guide them as to what they are most likely to come to, and, in fact, to give them a chance of finding out their bearings for themselves. Dr. Johnston is quite unique in the efforts he makes and the sympathy he shows in trying to place his boys, but that is not practicable in most schools and with most headmasters. Whatever may be said about the expense of the present educational system, I believe that it would be well worth while, though it would involve considerable expenditure, to devise some means by which advice could be given to quite young people at an early age as to their careers. With the present economic conditions, once a youngster gets into a job he finds it difficult to move from that particular trade. So the importance of getting him right at the start is very great; and if a mistake is made he will probably be discontented and a source of dissatisfaction both to himself and to everybody around him. That particular feature of the paper is of great importance and bristles with difficulties. On the question of training, I would urge that a boy should complete his training in the

works if he is going to manufacture, because he has become identified with some work or job, he knows the people around him, and if he is worth his salt he has prima facie made a niche for himself. If he breaks off at that point to return to college he is throwing away a very valuable asset. The outstanding point that one looks for in connection with young people coming from the university is personality. The man who has not to refer to a book whenever he is faced with a new proposition, the man who can fall on his feet like a cat and go on without even looking round, is the type of individual we look for to carry on the work of engineering when the rest of us drop out. The question of imagination is also important. It must be imagination tempered with a good deal of experience; in fact, what is wanted is the individual who has his head in the clouds but keeps his feet very solidly on the ground.

Prof. G. Stoney: The author says: "Unless each of us is striving to increase the common good he were better dead." Does he mean that we should kill off all the old people, invalids and incapables? It is undoubtedly true that an engineer is born, not made. We can make them only to a certain extent, and only the fitter ones should enter the profession. To be an engineer a man must have an eye for proportion—a great many never get that—and must be able to make things simply and cheaply. The engineer is a man who does for a shilling what another person does for a pound, and no theoretical training will give him that power, although such training is a great help. Another point which the author touched upon was that besides dealing with machinery he must be able to deal with men. A successful engineer must be able to influence others who are under him and be able to induce the directors and others over him to see that his schemes are good. Without that he will never get on. There is a difference of opinion as to whether the shop or the college should come first. I myself plead for a certain spell of shop practice associated with part-time study. Many of my best men have first gone through our day-apprentice course, under which for two years they came on Mondays to the college and spent the rest of the week in the shop. Others have gone to evening classes to continue their education before entering college. There is no need for a total break between the school and the university; with shop practice in between they can carry on, especially by means of the day-apprentice class which, I think, is one of the greatest boons we have in this city. The young man who comes into the works at, say, 16 years of age is much more adaptable to shop life. He rubs up against the workmen, and the workmen are much more ready to speak to him and show him things. He gets that most valuable factor, the opportunity of knowing the British workman, without which he will never be able to get on in the world. A large part of one's work is dealing with the British workman, appreciating his position and feelings. The capacity for drawing safe deductions from experiment and experience and for seeing what limits there are is most important. This is absolutely necessary if progress is to be made. If a man is not able to make safe deductions he is nothing more than a "walking slide rule." The author mentioned that extrapolation is dangerous. Without it, however, we cannot make any real progress and go from a smaller thing to a large one. I have seen turbines go from 50 h.p. or 32 kW to 50 000 kW with extrapolation, and in 20 years electrical engineers have made it possible for alternators at 3 000 r.p.m. to rise from 750 kW to something like 20 000 kW. Would that have been possible without extrapolation? The man who can safely extrapolate is the man who makes real advances. I am glad to see that the author calls attention to the importance of a wide knowledge. It is curious how often a knowledge of things totally outside one's general line of work becomes of immense value. During the war I had to provide for the billeting, clothing and feeding of large numbers of men, and I was largely occupied during the first year of the war in turning old warehouses and old workshops into billets. A small knowledge of sanitary engineering, though entirely outside my usual work, became of immense value.

Alderman W. Walker: I do not agree with the author when he says that a schoolmaster should decide what careers the boys at his school ought to follow in their after-life. For such a scheme to be successful the schoolmasters of this country would have to possess a fairly precise knowledge of all the principal industries and the qualifications and mental equipment required by those entering them, if they are to have a reasonable chance of success. The intuition and the ability to judge correctly cannot, I think, be taken for granted as being either a natural gift, or an acquired accomplishment of schoolmasters as a class; yet, without these, an attempt to place such a momentous decision in their hands could not be successful. To-day most parents do take an interest in their children, and give much thought to what their future careers should be. They listen to a boy's ideas, they can watch his tendencies, and the father can usually get good advice from friends engaged in a particular career to which consideration is being given. Parents are anxious not to make a mistake and can often bring factors into consideration of which a schoolmaster does not know. Obviously he should be consulted. I think that the figures which Mr. Jones gave us of the percentage of ex-students from Manchester and Leeds who, trained as engineers, are to-day, to the extent of 50 per cent, engaged on the administrative side, were most valuable. These figures are very significant but I am not astonished to find the percentage is so high. It proves how necessary it is that during the period of training the engineer-to-be should have an opportunity of getting an insight into the administrative side of the industry. I am afraid it is one of the weak points in most schemes of training that the opportunities for gaining that insight are infrequent and very often not to be obtained at all. I have been engaged with others in drafting a scheme for the training of power station engineers. When we had completed our first draft we sent it to the boards of the 13 districts into which the United Kingdom is divided. These 13 boards consist of representatives of employers and of the technical staffs, and we asked them for their comments. We have finally worked out a scheme which gives two lines of approach to the status of power station engineer. One of them is for the boy who starts in an elementary school.

Such a boy will go for one term to a secondary school, then to a manufacturing works for a period of 5 years, after which he will spend two years as trainee in a power station. The other is for the boy with a public school education followed by a three-years' university or technical college course, and then either one or two years (that point is not quite settled) in a manufacturing works, finishing his training by two years in a power station. Those who have been trained by both methods respectively must then pass the Associate Membership Examination of the Institution of Electrical Engineers to qualify as power supply engineers on the register which will be kept by the National Joint Board for the industry. As years go on it will be very interesting to note what percentage of the men who have gone through these respective courses will make good by obtaining the higher positions in the profession. It will certainly be some test of the value of the two methods of training, but to-day it has not come into being. Another point brought out by Mr. Jones is one with which I strongly agree, viz. that youths who have had a college training which has taught them to think and draw deductions and to make proper use of information, will probably be more successful than those who have not had such an education. For example, how many students have gone through the School of History at the Manchester University and have subsequently made good in industries and in walks of life entirely detached from history. They were taught to think, to investigate. to use and develop their mental powers, and that is the key to their success in life. They have been able to apply those methods to other problems. It is this fundamental training, added to the purely technical training, which counts for much. It is one of the tragedies of the profession to find large numbers of men who, whilst highly successful as technical advisers, will never be able to take high and administrative posts. They have not the intuition which enables them to visualize what line any given development will follow nor the commercial sense to perceive the ultimate effect of a line of action decided upon at the present. When the main decisions have been taken and the policy has been decided they are then able to deal with the purely technical points. I think that employers in the industry should give more opportunities to the younger members of the technical staff to get an understanding of the organization, administration and commercial sides. Opinion as to the necessity of having works experience is unanimous, judging from the fact that not one of the 13 district boards did not lay down as being essential to the career of the power supply engineer that he should have had a period of training of 5 years in one case and 2 or 3 in the other in the works of a manufacturing engineer before coming into the electrical supply industry, the idea being (and I agree with it) that a youth in a power station who has not been in an engineering works and there learned how the plant is made, methods of manufacture and the handling of machines and the use of erecting tackle, is not likely to become a successful power station engineer.

Mr. J. W. Thomas: I should like to say a word or two on several aspects of the paper that have not yet been touched upon to any extent. Very little has been said about the engineer's due, and it is the point which interests me most. As Prof. Miles Walker has remarked, it is not the predominating feature in the engineer's life but it is an important one. The engineer plays a great part in industry; in fact, as the author reminds us, civilization would practically come to an end if the engineer ceased to function, and because he performs that useful function he is entitled to due consideration. I do not think the engineer has ever expected, and does not now expect, anything unreasonable in the way of reward or recompense for his work, but he does ask for a return that will enable him to live a decent and respectable life. Perhaps he is too much engrossed in his work to give sufficient thought to what he is getting for it, but, after all, like all other human beings he has to live and is therefore entitled to something that is commensurate with his worth. He does not require a very large salary, because his happiness is in his work and does not depend primarily upon his reward, but he requires sufficient to bring up his family respectably and under decent conditions. When that has been settled an engineer will do his work much better, for no man can do his work effectively while he is embarrassed by financial difficulties. I can say quite confidently that there are many engineers, certainly in the electricity supply industry, who are doing their work with more efficiency and greater contentment to-day because their remuneration has been settled on a satisfactory basis. The engineer's due does not, however, consist merely in his financial reward, but in the recognition of his status in the community as a professional man. Though to perform his work he requires as much skill, training and knowledge as members of other professions, he does not get from the community the same recognition and status that they enjoy, nor is it regarded as being necessary that he should be governed in his professional life by those rules and codes of conduct which are the outstanding features of the older professions. There is no reason why engineers should not have the same professional standing and be accorded the same prestige as the members of the professions of law and medicine, seeing that not only do they require careful training but that they give to the community equally important service. Their lack of status in the past has been due partly to their own inertia, but chiefly to a lack of faith in themselves. They do not think sufficient of their service to the community. I mean to imply by this not that they ought always to be sounding their own trumpets, but that they ought to have a larger and juster view of their own worth. If the responsibilities of an engineer in charge of a large power station which controls the lighting, power and transport of a city, be compared with the work of a lawyer in his office, or even of a doctor, it will be agreed that the engineer deserves at least the same standing and recognition as they enjoy. I am in agreement with the author in regard to the choice of men for the engineering profession. I disagree with some of the previous speakers because I believe our methods of choosing men for the profession, or of allowing them to enter it, are much too haphazard. The difficulties of choosing men are undoubtedly great, but they

are not insuperable. They are only great because we have not the data to work upon, and I am quite convinced if we had more data—something on the lines suggested by Alderman Walker—we should be able to prevent many people starting on an engineering career who would be better advised not to. My own experience has been comparatively short, but I know four men who have taken engineering degrees, two of whom are now practising in medicine and two are engaged in the cotton trade. I have no doubt that many members present have similar knowledge of people who have started well in the engineering profession but have found it uncongenial and have then turned aside to some other walk in life. It seems rather serious that they should have gone so far and then be lost to the profession, when a little more systematic selection might have avoided it. Turning to another point, I am convinced that there is plenty of room for the engineer in public life. I always regard him as the true thinker in the community, a man who is bold in conception, is not afraid of taking risks, and who can see a problem and tackle it. That is the kind of man who is wanted to solve many of our industrial and economic problems. If I may refer to another profession, the lawyer who dominates our public life is not, by his training, a man calculated to tackle a problem on new lines; he is not essentially an innovator. Admittedly he has an important function in society inasmuch as he gives form and expression to the views of the community, but he is apt to look to the past for his solutions, whereas the engineer is always tackling problems on new lines. If engineers would not keep their noses so closely to the grindstone, but would take a larger view of things, and see that there were big public questions to which they could make an effective contribution, I think our industrial and economic life would be the better for it.

Mr. M. Hird: The author has instructed us fully in our duties, the chief of which, and the one that has had the most attention paid to it in the discussion, is in regard to the choice of the engineer. There is a great difference of opinion as to how the engineer should be chosen, but it is generally agreed that we want the very best that is obtainable. We must make the choice; no one else can do it for us. The citizens of Ancient Rome at one period of their history used to keep Greek slaves to do their reading and writing for them and it was supposed to be bad form to have the accomplishments of a slave. We are in the same position as those learned helots, as we might call them—we have made all the apparatus of latter-day civilization and handed it over to other people to use. The reason why we do not get our status talked about, as mentioned by Mr. Thomas, seems to be that the whole of the products of our work ultimately passes into other hands. It has been mentioned that half of our number go into administrative work after having had their engineering training, but I think that in spite of all the labour questions, works committees, welfare schemes and the like, we have all had our training in dealing with the raw material provided by Nature. Nature is honest, even if at times she is somewhat pigheaded. This in itself makes it difficult for us, as a class, to deal with humanity —which is pigheaded as well. We cannot avoid taking some responsibility for the ultimate results of our handiwork, and I think that one reason why we feel so helpless before this sort of question is that we have paid so little attention to questions of this class. I suggest it is our duty to think more about the ultimate results of the work we are doing, and in the course of time if we give these questions serious consideration we shall be able to speak as a body and what we say should command respect.

Mr. T. E. Herbert: Far too seldom are we asked to study ideals and to get down to the fundamental problems of life. The author has considered the special case of the engineer, but would it not be better to say, in set terms, that we want everyone to do the work that he is best fitted to accomplish? Such work involves his natural aptitudes, and in doing it he will find not only the greatest measure of usefulness to the world in general but the greatest happiness to himself. The author says, in effect—quite rightly in my view—"First catch your engineer young," but apparently he thinks the schoolmaster is the right person to make the selection. I agree that a schoolmaster is a member of a very important profession, but the work of finding out what are the real capabilities of a youngster seems to me to be entirely a job for the medical man who has specialized in psychology. In my opinion the new science of pyscho-analysis developed by Freud, Jung, Adler and others will advance to such an extent that from the hands of medical specialists one will ultimately be able to get a correct forecast of what profession a boy should follow. This, however, is essentially work for the specialist physician. The body and mind are, of course, related and we must get the right people in the right places, and not round pegs in square holes. The governing motive in getting through life may be simply money, or it may be fear alone that drives a person to perform his duties. In either case he will not perform his work with happiness to himself, and if he is not happy in his job then I do not think that very much can be expected in the way of results. With regard to the training of engineers, one point which should be emphasized very strongly is the vital importance of the human touch. In all but the very early stages the majority of engineers are called upon to guide and direct human effort. The ideal to be attained has been described as:—

> "Souls tempered with fire,
> Fervent, heroic, and good,
> Helpers and friends of mankind."

The mental attitude may be correct but it needs a considerable amount of training in the administrative side of the work to achieve a successful application of the principle. A little later in the paper the author refers to a subject which interests me very greatly, i.e. the need for an accurate knowledge of English and power of expression so that reports, letters and statements may convey to the recipient a perfectly clear idea of what is intended. On the other hand I think that the young engineer should acquire the judicial frame of mind referred to by Alderman Walker, and should

appreciate the dignity of his position. The use of extravagant language is perhaps an error into which young people are prone to fall. If an engineer enters into a newspaper controversy with a professional colleague he ought to remember that by using wrong methods in that controversy he brings his profession into the profoundest contempt. Such a controversy does untold harm to our profession and that is perhaps why in so many cases a so-called business man instead of an engineer is found in administrative control of an essentially engineering concern. It may be that some engineers have no administrative ability whatever, but I do not think it is fair to say that because a man is an engineer and knows his work he is *ipso facto* unfitted for supreme control. Take, for instance, such a job as that of a director of a railway company. The very last thing that any director of a railway company has is a knowledge of civil, electrical or mechanical engineering. I do not see why that sort of thing should continue to the same extent as it has obtained in the past. It may have been our own fault and if we have people in our profession who do not realize the proper use of the English language and the proper attitude towards their professional brethren then very serious damage to the prestige of electrical engineers will result.

Mr. J. B. Hartley: In the first Section of the paper, dealing with the rights and duties of life, the author mentions that we should try to do a little bit more than our duty. That reminds me of the need for enthusiasm. We can never do more than our duty if we cannot maintain our enthusiasm; we all enter the profession with it, but somehow many of us lose it. Whether it is our fault, the fault of the modern industrial system, or the fault of the people who employ us, it is difficult to say. The man of real enthusiasm puts his soul into his work, not because he loves his work for itself, but because the idea behind the work has made him captive. A so-called matter-of-fact man, who prides himself upon taking things as they are, who has no use for theories, dreams or speculations of any kind, is never an enthusiast; in fact he scorns enthusiasm as a stigma of an ill-balanced mind. We have all met the man who is sure that an ounce of common sense is worth a ton of enthusiasm. No great ideal ever tempts him from his moorings. He may be a faithful, industrious, intelligent worker all his days, but his career in his profession or business will be commonplace and uninteresting. Such men often make the best of neighbours and citizens but they do nothing to make the earth a better place on which to live. Enthusiasm is one of the most dynamic of all human qualities. In a sense it is the ideal descended on earth to battle with realities; men instinctively recognize its high origin and easily surrender to its influence. That is why we say that enthusiasm is contagious. A business organization lacking enthusiasm does not, I am sure, get out of its men 50 per cent of their potential efficiency. We all start with enthusiasm but many of us lose contact with this very effective driving force. It is not always our fault; it may be due to the men who have control of us. Executive officials do not always help to keep an organization loyal and enthusiastic. New positions should, whenever possible, be filled by the promotion of employees rather than by going outside for new men. Managers often handle their men stupidly, not seeking to make each employee feel contented and hopefully ambitious. Each employee should feel that his welfare is of interest to his employers and that they are determined that the merit of not a single one should be overlooked. So far as men are concerned, I think we often get the wrong mental attitude towards our work. There is one degrading conception of our work which should be avoided by engineers. Many engineers speak of their positions as "jobs." This conception often leads a man to think of his work as being a more or less disagreeable occupation for 8 or 10 hours a day. The typical man with a "job" very soon begins to think that he is overworked and underpaid, and is glad when the day is over, for the job means hard work and no pleasure. He also has a habit of thinking that mere length of service alone entitles him to promotion or increased remuneration. He usually has a special grudge against his immediate superior, the man who directs his work. He is sure that he works harder than his superior but that his work is not appreciated. There is a sense in which every task is a gold mine. The man who works for the gold in the task rather than the amount in the pay envelope is the one who eventually makes most progress. In Section (5) the author reminds us that we should be ready for opportunities. It is, I believe, a familiar human weakness to think of ourselves as not being in just the right place. We are prone to think that opportunity, like happiness, lies in some distant place, and if we could only get there we should be successful and content. Actually the best opportunities often turn out to be close at hand. This is perhaps naturally so, for we are familiar with near-at-hand conditions and know their possibilities. As Thomas Carlyle has said: "Our grand business is not to see what lies dimly at a distance, but to do what lies clearly at hand."

Mr. L. H. A. Carr: Many of the questions raised by the author are very profound. He refers to the right to live, but is there any right to live without a corresponding right and duty to work? There is an essential difference between ourselves and the members of some of the other professions which have been mentioned during the discussion, and this difference must be taken into consideration in discussing our due and our duty. This difference is due to the fact that an engineer does not carry out single-handed the ideas of his brain. In almost every case a large number of workers are required to carry out his designs. Consequently the present system of organized industry has arisen in which the majority of engineers are not individual practitioners, but are closely allied to a large number of workers of all classes in order to form an industrial unit. Further, and largely arising out of the same facts, the engineer's duty is not served directly to, nor is his due received directly from, individual members of the community who require his services, as is the case in many other professions. This brings up the whole question of the organization and financing of industry, which in a sense is a side issue to the subject of the paper, and yet is one that would have to be thoroughly discussed in considering how the engineer's duty to the community can best

be carried out. Among the necessary qualifications for the embryo engineer, the author has omitted to mention good health and a strong constitution. He suggests that more use might with advantage be made of engineers in connection with the solving of the many problems with which industry is faced. This view is held by many other engineers who have already formed professional organizations, one of the objects of which is to promote such practices. One other duty of the engineer has not been mentioned in the paper. In feudal times the inhabitants of a village were almost entirely dependent on their overlord, and, whether he realized it, or whether he shirked it, his was the responsibility for seeing that they did not starve in bad times. I feel that this responsibility has, to a large extent, come down to us, and that we are responsible to the workpeople in our industry for getting sufficient work into our factories to keep them from penury and starvation.

Mr. A. E. Clarke (*communicated*): I have often thought that the papers read before the Institution have been too much confined to the technical and professional side of engineering, with consequent neglect of that equally important phase, the contact of the individual with the world at large and the reactions that spring therefrom. It has been well said that "it is a consolation that life is still the same essentially as it always has been, and that we are still the sons of men, and not the children of machines or systems." It is also interesting to note the accuracy with which the character of the modern engineer was forecasted in the apocryphal Bible by the writer Ecclesiasticus. Writing of the activities of the farmer, graver, ploughman and so on, he proceeds thus :—

> "Without these a city cannot be inhabited.
> And they shall not dwell where they will, nor go up and down.
> They shall not be sought for in public counsel.
> Nor sit high in the congregation.
> They shall not sit in the judge's seat.
> Nor understand the sentence of judgement.
> They cannot declare justice and judgement.
> And they shall not be found where parables are spoken.
> But they will maintain the state of the world,
> And all their desire is in the work of their craft."

The whole excerpt fits the engineer, the last two lines being particularly applicable. This, then, is the man whose duty and due are under discussion. Should not the "duty" come before the "due" in the title of the paper? It is only by the performance of duties that dues or rights become established. Also, the last sentence in Section (1) should be altered to read "There is no duty without its corresponding right," and it is in the spirit expressed in this word inversion that many, if not all, of our industrial troubles to-day may be solved. Once this principle has been clearly grasped, and is in process of resolute enforcement, confidence between man and master, community and individual, will be established and most of our difficulties will disappear. It is said that the spirit of the engineer is expressed in the single sentence "I will," i.e. he is essentially an objective thinker as opposed to the subjective thinker, who says "I am," and it is because of this that the engineer's activities permeate the whole of the world to-day. There is hardly any action which can be taken or thing that can be handled that has not been influenced at some stage by the work and thought of the engineer, and accordingly civilization, as we understand it to-day, is largely founded on, and is certainly maintained by, his efforts. His duties, therefore, are very arduous, for on his energy depends all the good that has survived from the past, and the development for the good of humanity at large of all resources which may become available in the future. Such a responsibility should make him very humble, and should serve to strengthen his determination never to cease to strive for the truth, speaking in the widest sense, both objectively and subjectively, as a member and perhaps guider of the human race, perpetually straining towards one goal, the betterment of humanity. His dues are therefore clearly established before the whole world, though, because of his peculiar concentration on his art, there has yet to grow up in the body politic a true appreciation of his worth. But if engineers will be true to themselves and indeed strive wholeheartedly, honestly and continuously to do their duty, not as mere engineers, but as conscientious members of the race of man, then there can be no doubt that appreciation will eventually arise, and they will be called on "to decide the courses and steer the ship of civilization to fairer seas." Signs of that change are already visible, and engineers are being consulted more and more widely upon all manner of diverse subjects. I do not mean to say by this that engineers are omniscient, because they must always remember that even to-day they are like Carlyle's minnow, which, although it knew every crick and cranny of the little piece of water in which it swam, had no conception at all of the mighty external forces of rain and sea which might at any moment in a (to him) terrible cataclysm sweep him and his world away to nothing. We are the minnows, the creek is our tiny world and the mighty influences are those forces which we do not even begin to understand, which work with æons as their unit of time. Up to the present the work of the engineer in public life has been but small, for the clear and simple reason that he deals with inanimate things and forces of which to some extent he knows the properties and can calculate the interactions, and which, within certain well-known limits, he can direct and guide to perform different kinds of acts. If he be a true engineer at heart, his work is of such surpassing interest and engages his attention so fully that he has neither time nor desire to enter the mazes of public life. Even if he be inveigled away eventually from his bench or his desk and is confronted with the *genus homo* with all its psychologic limitations, he finds that this particular being will not run true to formulæ and he becomes possessed of an impatience, evolved from his very training and experience, which eventually causes him to turn away from such recalcitrant material and return to his well-beloved, well-understood and obedient forces of Nature. This is a limitation which engineers in the future will have to surmount, and

it is refreshing to find such stress being laid on this point both here at home and in many countries abroad, particularly America. In that country I understand that concurrently with technical courses at the universities, courses in natural philosophy, economics and certain branches of psychology are included. Years ago a paragraph appeared in *The Spectator* which struck me as being inherently unsound. It was as follows:—" The design of learning is, I take it, either to render a man an agreeable companion to himself, to teach him to support solitude with pleasure, or, if he is not born to an estate, to supply that defect and furnish him with the means to acquire it." If the whole of the objects be included in one course of education then there is little to cavil at, but to take either part separately and to compare each with the principles enunciated by the author reveals at once the infinitely greater charity and broadness of conception of the author's scheme. Stress has been laid on the selection of engineering students and trainees, and rightly so, but I do think that when advising prospective engineers, greater stress should be laid on the extremely arduous nature of the training necessary, both physical and mental, and the long years between the ages of 20 and 30 which return little to the devotee and demand all his endurance. Many young engineers seem to give up hope and lose enthusiasm between those ages. To the chosen, such years act as a kind of weed-killer and exorcise all the weak elements of character and endurance with which they may be cursed. Nevertheless, a deal of heart-searching and, perhaps, bitterness might be spared if greater stress in advice were laid on that period and students were warned of what to expect before they entered the ranks of the profession. Employers should treat men during those years with much consideration, encouraging their efforts and guiding their steps gently towards the shining light beyond. Another equally important matter is the selection of the trainers of students. It has often seemed that college professors, the experience of many of whom is confined almost entirely to practice in college or school, must necessarily lack certain qualities which are of supreme importance to the budding engineer. The dispensation of knowledge on the subject of the great and unchanging fundamentals of engineering may be safely placed in their hands—that is their training—but it does appear that better ends would be served if on that stock were grafted a selection of modern practising engineers who would deal with engineering in its most recent applications in industry and would bring to bear on the students some of those great qualities which have lifted them to their present heights.

Mr. W. J. Medlyn (*communicated*): In Sections (3) and (4) the author quite rightly stresses the importance of technical knowledge, but very little is said about the need for training in administration. It is true that many engineers are required to be technical experts without having to exercise powers of administration to any considerable extent, whilst the duties of other engineers may be chiefly administrative. The discussion has brought out the fact that a very large proportion of trained engineers do ultimately take up important administrative posts; and in this connection I think the following brief extract from an address delivered in 1907 by Mr. James Pigg, then chairman of the North-Eastern Centre, could be usefully placed on record:—" Another essential qualification of the engineer is the power of organization. Organization can only be effectively carried out when a clear view of the end to be attained is combined with a thorough knowledge of the means available. Effective organization implies a knowledge of the tools; the aptitude to judge a good tool from a bad one, or the ability to improve it. These tools are for the most part men. The engineer must therefore be a good judge of men, and know in what way they may be most effectively used for his purpose; how, in fact, they may each be fitted properly into the mosaic which it is his business to form." From the observations in the present paper I gather that the author is in full agreement with the remarks I have quoted, but it seems to me to be well worth while to emphasize the importance of these qualifications. There is, of course, room for the best men of both types to rise to positions of eminence. Whether the technical expert or the engineer-administrator reaps the greater reward for his labours is perhaps a matter for speculation, but on the whole I am inclined to think that the greater possibilities for advancement lie with the administrator. In both cases, of course, success can only be achieved through hard work and self-sacrifice.

Mr. T. Petrie (*communicated*): The author's two main themes, put very baldly, are that engineers must be born to be made; and that when they are at the height of their powers they should turn more to public affairs than they do. With regard to the first, it is probable that every boy at one stage of his life has wanted to be an engineer—or at any rate an engine-driver—and it always seems a wonder to me that more do not start engineering training than is actually the case. With regard to the second, I think the same may be said of all the intellectual professions—except perhaps the Law. The whole of one's active mind is absorbed in keeping abreast with one's profession, and the time devoted to outside work means a loss of efficiency as a professional engineer in the strictest sense of the words. Nevertheless, we have had two engineers as Lord Mayors of this city within the last three years, and both of them are exceptional men. I should like to stress a third theme for the fundamental duties of an engineer. He should never take anything for granted—not even a formula. His training should be such that he learns not only his fundamentals but also how to think for himself, so that when new problems arise he is equipped to meet them with an open mind. Our immediate predecessors of the Victorian era, if they had a fault, were rather prone to accept blindly the lead of the big men—even shops tended to be run on the principle that what was good enough for their grandfathers was good enough for them. The consequence was that new ideas—in other words true progress—tended to be stifled, to the general loss of the community. I am afraid that the big men were as much to blame as the others—at any rate Herbert Spencer, replying to some new argument, is reported to have said: " That can't be true, for otherwise my ' First Principles ' would have to be re-written —and the book is already stereotyped."! How far is

this attitude true to-day? We all pride ourselves on modern progress and broadmindedness—but I should like to stress this aspect of the question and to suggest that if they want to represent all that is highest in their profession, engineers should always think things out for themselves and then act on their convictions.

The Author's Reply to the Discussions at London, Liverpool, Newcastle, Leeds, and Manchester.

Mr. T. Carter (*in reply*): Mr. Dunsheath says that the Papers Committee may have had some misgivings about accepting "a paper so unorthodox as this." I certainly had misgivings as to its reception, for it might have been thought by those who heard it to be more suited to the pulpit than to the reading-desk of the Institution and its Local Centres; but the volume and the sympathetic tone of the discussion are the best proofs that there is a place in the Institution for the stirring up of thought on fundamental issues, and I trust very sincerely that others, far more versed in these great matters, and far better able to deal with them than I am, will from time to time submit them to us for consideration. I believe that the Institution, with its ever-increasing weight of influence, could so shape and educate public opinion that a proper view would come to be taken of the rightful place and standing of engineers in the community. The mere existence of our Institution, and of other kindred Institutions, is evidence, to those who understand it, of the real importance of the matter; and it might be possible to do a great deal through the Engineering Joint Council to secure a fuller study of the whole question of how to use our human resources adequately. The paper, and the discussions arising out of it, have necessarily dealt in a very general way with what are really the mere outlines of the subject; and my reply must be on equally general lines. Had I unlimited time and ability to think out all that has been said, and had I unlimited space to fill, there would even then not be an end of what could be written. But there are limits, and it is well; for there is the day's work to do, and we may not cease from it while we consider how to do it. Is not that all the more a reason for the early acquisition of a clear view of fundamental principles, so that, as far as in us lies, we may deal with the unending chain of events instinctively in the best way?

I propose to make one reply to these five discussions, and if I do not specifically mention the name of every person who took part in them, it will not be thought, I am sure, that I have not heeded what he said. He will find, I hope, that I have referred to the essential things in his remarks. It has been interesting to discover, amongst much agreement with the principles laid down in the paper, that questioning and controversy have centred round a few definite points. I think the thing that has impressed me most is the readiness with which one person after another has assented to views that are nothing but sheer idealism and counsels of perfection. Matter-of-fact and prosaic as are the work of engineers and their attitude to its problems, there is in far more of them than might be expected—deep down perhaps, and rarely seen at the surface—a poetic outlook that will surely save the profession from ever becoming a merely materialistic affair. Thus we may escape the all-too-common tendency to be taken in by "that great engineer, Satan," the eternal adversary of God and man, who lays his snares so cunningly. He is the champion of the second-best: "Doth Job fear God for nought? . . . Thou hast blessed the work of his hands. . . . But put forth Thine hand now, and touch all that he hath, and he will renounce Thee to Thy face." What could more perfectly express the dullness and deadness that sometimes steal over us than these lines by Humbert Wolfe, taken from *The New Statesman*?

IN THE CITY.

In the City they sell and buy,
And nobody ever asks them why.
But since it contents them to buy and sell,
God forgive them! They might as well!

Mr. Swinburne carried the discussion to a place of wide outlook; he raised the whole question of the kind of education that will make the men and women the world needs, and he brought into view no less a thing than democracy itself. In spite of the change in the attitude of the educated towards the uneducated—a change that may perhaps be symbolized by quoting, on the one hand, the command: "Be silent, all flesh, before the Lord," and, on the other, the pleading petition: "Come unto Me, all ye that labour, and are heavy laden, and . . . learn of Me"—it is to be feared that democracy has far to go before it ceases to deserve Mr. Swinburne's definition of it. It is an epigrammatic definition, and must be read accordingly; but it is not quite clear whether the governors are meant to be described as the greatest fools amongst a community of fools, or whether they are to be looked upon as the least foolish of the fools, great, though fools; great, if they are indeed real and noble leaders, in spite of the tincture of folly that they cannot escape. I hope it may be believed that the second is the true alternative. Although it is necessary to admit the inevitability of a pessimistic view of much that is human, and although it may be no more than a feebly flickering and perhaps apparently quite illogical hope that yearns for a brighter goal, I trust that we may cherish the little spark as often as we find it. Who knows when it may break out into a great conflagration of soul-searching and purifying enthusiasm? You remember how, in Hans Andersen's tale of "The Flax," the children "sang over the dead ashes:

'Snip, snap, snurre,
Basse lure:
The song is ended!'

But the little invisible beings said, 'The song is never ended; the most beautiful is yet to come.' Only the children could neither hear nor understand this, nor should they; for children must not know everything."

I had naturally to confine the paper to problems peculiar to engineering, but it is quite true that in its essentials it applies to all callings. I am sorry that Mr. Day is disappointed on this account, because it seems to me that unless the engineer is facing life fundamentally from the same standpoint as the rest of men, he will be living in a world so different from theirs that he will have less in common with them than he ought to have. I quite agree with Mr. Day that what is desirable for the engineering profession is equally desirable for all others, and I would emphasize Mr. Herbert's point that what we want is that everyone should do the work he is best fitted to accomplish. The order of words in my title has been criticized: duty, it is said, comes before due, and I gather too that my definition and discussion of the engineer's due is thought by some to be not practical enough. Apart altogether from the fact that an inquiry as to whether or not the engineer is duly paid for what he does would be quite inappropriate to this occasion, I think that there is a far wider view to be taken of both the points that have been raised. Due, I suggest, begins at birth, before any duty can have been done to form a claim for due. The engineer baby (no one knows as yet that fact about him) has his due in the bodily and mental food, the clothing, and the shelter that his parents, or failing them the community, try to give him. It is only as he grows up that he realizes that duty is the counterpart of due, and, if he is a decent citizen, does his duty. In return for that, he continues to receive his due, that is, his opportunity for a proper life, as long as he is serving the community to the utmost of his strength. So, though due and duty are inseparably linked, I put due first because it is first in time. My reason, too, for saying that rights have corresponding duties rather than that duties have corresponding rights, which is also true, is that to-day it seems that many are clamouring for their rights and forgetting their duty altogether. So I want very definitely to stick to the order of the words in my paper. Then, as for the engineer not getting a salary commensurate with his deserts—a subject, as I have said, that may not be discussed in detail here—I would say that his surest way of getting all that he should have in that direction is to see that he and, as far as he has influence, every other engineer strive primarily to make it absolutely clear to the whole community that they put the interests of the nation before the interests of their profession, and that they equally count their profession greater than the individual engineer, infinitely important as every human soul is. If this seems to be a distant goal, I can only say that I believe that disinterested service will tell in the end, and will establish the engineer on a far safer basis than anything else will. Here, as so often, the longest way round is the shortest way home. This seems to me to answer Mr. Hurlbatt's point about the group and the individual: to consider the interests of the group, or rather the whole, is to me the soundest way of advancing the interests of the individual. I fear that I am expressing my meaning crudely; it is put perfectly in the words: "Be not therefore anxious, saying, What shall we eat? or, What shall we drink? or, Wherewithal shall we be clothed? . . . Seek ye first the kingdom of God, and His righteousness, and all these things shall be added unto you."

I agree with Mr. Wadeson that we must decide what is the common good, difficult though it is to discover it. If we say that it consists of all that helps the race rather than hinders it, we do not say more than is obvious; the real problem is to get a wide enough view of things to foresee whether they will help or hinder. Prof. Stoney asks whether I would kill off all the old, the ailing, and the feeble. Emphatically no! There are old people without whose guiding we should be lost; there are those whose bodies ail and yet whose courage is an inspiration; there are feeble folk whose presence is a benediction. All these are somehow contriving to increase the common good, so let them live, and do not cease to thank God for them! If there be a rubbish heap somewhere in the universe, it is not they who will be cast upon it in the last reckoning. But, after all, I do not think that I proposed to kill off anyone, by means of the lethal chamber or otherwise. It is not advocating the slaying of a man to say he were better dead; nor is it suggesting the use of the lethal chamber to say that it would be more comfortable than life. Again, when I described some rocks as unclimbable, I meant them to be thought of as unclimbable, and not as climbable with difficulty. Those who have referred to this have scarcely misunderstood me, and I am grateful to them for having made explicit what I said only implicitly. The same thanks are due to those who have mentioned the essential importance of never doing a thing ourselves if we can find someone else to do it well for us. The managing director does not lick and stick on the stamps that frank his office correspondence; that is an obvious illustration of the principle, and it is according to our skill or want of skill in devising less obvious applications of it that we shall be free for bigger things than we have been doing, or, on the other hand, stuck in a morass of clogging details.

A good deal has been said about my reference to free meals and other free things (which, as has been pointed out, are not really free at all, though it may be recalled that they are not usually paid for, in the ordinary sense, by those who receive them). Had I put the word "education" inside quotation marks, as I have just done here, or described it as "education, so called," my meaning might have been clearer. It is because we are inclined to regard these things as sufficient, as solving our problems, as ends rather than as means, that I suggest that they are likely to lead to so inadequate a use of our human resources that they are only to be thought of as bringing death to the nation in the end. I agree with Mr. Vernier in what he said about doles, but I feel sure that he agrees too that they are a very dangerous expedient and a most regrettable necessity.

I am glad that Prof. Scholes has given the American definition of engineering, because, although human activities are really amongst the great sources of power in nature, it is perhaps well to mention them separately. To direct and organize them aright calls for all that is most skilful and cultivated in the engineering brain, and I have tried to indicate in the paper some of the

things essential for success. I gladly add to these the others that have been mentioned in the discussions: enthusiasm, imagination, general knowledge of men and of human character, the possession of the human touch, good health, a strong constitution, the enlightenment that comes from foreign travel, and the acquisition, somehow, of common sense, by which, though I am never quite sure, I suppose is meant that most uncommon thing, a nice appreciation of the universal judgment on affairs. Equally gladly will I add the sales engineer to the list of persons making up the total of our profession. I agree with Mr. French's classification of the sales engineer, and I pass it on to Mr. Allan, feeling sure that it entirely meets the point that he raised. My own reference to the perennial question of the engineer-salesman was rather to the problem of who he is to be: that is, whether the qualities described by Mr. French are sufficiently often found combined in one person to make the supply of sales engineers equal to the demand, and whether, if they are not so found, the man who will sell goods best is the engineer as such, or the salesman as such. I think that this is a very real problem, and I believe that its solution is to be found along the lines indicated in the paper. Mr. Allan and I really agree with each other, and I most cordially endorse what he and Mr. Dinerman say about the extraordinarily useful results of the activities of the first-class sales engineer. Mr. Crompton asks me to add the mains engineer to the list also. I intended him to be included amongst those who run power stations, using the word "run" in the widest sense; but if that is not clear, I am quite willing to mention him specially.

I suppose that many papers could be written on the very wide subject of the finding of engineers, and I think that it has been referred to in the discussions more than any other question. Because there is so much that might be said, I must be as brief as I can in my comments. I value exceedingly Mr. French's proposal for the extension of the principle of collecting information about the characteristics of persons: if we could study representative men from the cradle to the grave, we should undoubtedly gain valuable data. I think his classification of engineers is most illuminating; it is the kind of thing that defines our aims and objects, and I am certain that it will be treasured by many readers. The difficulty of getting information about people in later life might be overcome—I say "might" advisedly, for most of us are quite unnecessarily casual about these matters—by explaining to students as they leave a school, a college, or a university, that they can be of service to their successors by continuing to furnish particulars of their doings and achievements to some central recording place. It is all very well to say that this kind of geometrical precision is impossible: perhaps it is in its complete details, but if it is desirable, as I believe it is, its impossibility as a whole is no reason for our not seeking to secure some measure of it. As I said in the paper, we must cease to be haphazard; and if by patient thought for the next few years we can discover how to do so we shall indeed have accomplished a great thing. I should not have dared to say what I did about finding out what is in children by intelligence tests, by vocational tests, and by continuous observation, had I not had in my possession the record of Dr. Johnston's successful achievement. It seems to me that it answers those who say that this cannot be done: a beginning has been made, and what with negative suggestions and positive suggestions, all carefully considered in the light not of a kind of laboratory analysis of the boys but of a friendly attention to their characteristics from year to year, there must be many men in a more suitable niche to-day than they would otherwise have been. I agree with those who would not trust the selection to schoolmasters as we know them now: most emphatically I agree. But if the demand for this kind of thing arises generally, the process of natural selection will gradually bring into the teaching profession those who are capable of doing what is wanted. It would be a great change; but it would not be any greater than, for example, the change in the methods of the medical profession in the last few centuries. These are not things to be reached to-day, or to-morrow, or even next week; but we shall not come nearer to them by saying that they are impossible. Our realization of their present impossibility is the first step towards their future achievement.

What has been said about the head-and-shoulders-higher-than-their-fellows people is interesting, and has brought out many valuable points. It may be recalled that I did not suggest discovering these to the exclusion of the second-class and third-class people; but I do think that we ought not merely to let them discover themselves. Cream, Mr. French says, always rises to the top; but it does not do so if we keep on agitating the milk and never give it a chance in the turmoil. We must provide facilities for the best men to rise to the top, and even if we discover them merely by letting them discover themselves, we still want to discover them. I said, too, that only by watching all will the best be found; and it is in the process of watching all that the second-best will be found too. It is clear that at Highgate every boy is helped as far as possible, and as far as he will accept help, and, given the right kind of observer, I am sure that the boy who needs least pushing will get it, and, on the contrary, much help will be given to those who need it most. We must get away from looking at things as they happen to be now, and transfer our gaze to things as we think they ought to be; thus will change follow change from less to greater perfection. All the more because, as the discussion has suggested, the first-class engineer might be almost a first-class anything, do we want to find out if he is just a little better engineer than he is something else, and say to him: Here is your finest calling. I would not make known the results of intelligence tests to all those who are tested. The data of mass tests are for the guidance of the teacher rather than for the information of the taught. But if I had to discuss the possible future careers of older boys with each of them personally, having had the opportunity of watching their individual characters and qualities, I should be quite prepared, at least by way of suggestion, to acquaint them with the results of my observations. Mr. Day asks me what I would do with the rest of the people. They, I imagine, will be those to whom I have referred as going through life doing mostly as they are

told, and they will have to be distributed amongst whatever occupations are in need of them, very much as they find room where they can now. Only, under a more careful system, they would be more efficiently employed. I quite agree that the question of population is wrapped up in all of this, but that is a problem that will apparently have to be tackled and solved somehow in any event.

I am still inclined to think that a restriction of the number of those who become engineers would be useful. That is not the same thing, however, as a refusal of an engineering training to some who will not become and do not intend to become engineers. Whatever they make of their lives eventually, it will always be useful to those who can afford it to have had an engineering training. It is reasonably certain, in my mind at least, that a smaller number of better-trained men would bring about an increase in efficiency. I agree that economic demands will regulate the supply, but with a lag, as Mr. Mouat Jones says. If the lag can be reduced by keeping records, I must say that I would advocate the keeping of records, for when the lag operates towards the throwing out of employment of those who have been trained at great cost, it is an undesirable thing. Hence the proposed register mentioned by Alderman Walker, Mr. Thomas, and others, is likely to be of immense use and importance, and the general question of the registration of engineers, mentioned by Mr. Marshall, should not be forgotten.

Under the heading of the training of engineers, many things have been said relating to the varieties of engineering education, with which my paper deliberately did not deal; I welcome them, because they add to the completeness of the discussion as a whole. I think that Mr. John's suggestion for a closer contact of teachers with practical work is particularly interesting and valuable, and ought to be seriously considered by those who have power to arrange these matters. I know that in some schools teachers are set free for travel periodically for a term of two, with beneficial results to themselves and to those whom they begin to teach again on their return. Of great importance, too, is the training scheme formulated by the Electrical Power Engineers' Association in co-operation with the representatives of the supply undertakings for the purposes described by Mr. Crompton, Alderman Walker, and others. Nothing could more completely ensure the smooth working of the supply industry, which is so vital to the general prosperity of the nation; it is a tremendous step forward, and one on which the industry is to be sincerely congratulated.

The great question of students living at home or away from home was raised: is it not true that some homes are far and away the best places for their children to be in, whereas other homes, or, better said, houses, are not fit for any children to inhabit? Reference has also been made to the relative share of parents and teachers in education. It is far from easy for even the most careful parent to get reliable information as to the best training and preparation for any kind of career for his children; and, if the schoolmaster were expert along the suggested new lines, he could render invaluable aid. With the best will in the world, parents are often puzzled, and their friends cannot always help them, nor ought they to be expected to be able to assist in complicated details. The schoolmaster need not know all the intricacies of all the possible vocations, professions, or jobs: these are roughly divisible into groups, and for many of them the general lines of preparation are alike. Here again, it is nothing to the point that the problem is difficult; it is far more pertinent to say again that one notable attempt is being made, with some success, to solve it, and that what can be done in one place can be done elsewhere. It should at least be easy to keep a potential Beethoven out of engineering, which is always something; and, little by little, finer distinctions will become possible and will be drawn.

I agree with what was said by Mr. Maccall, Mr. Dickinson, and others, about the value of internal examinations. They are obviously in a category quite different from external examinations, and the more their results are judged in the light of the general work of those who sit for them, the more will they be really a part of the record of achievement that is so much more desirable a basis of judgment. It is, indeed, in the long run, and the older a man grows, the only possible basis of judgment. So far as the general curriculum of a university or college training goes, I feel sure that the course suggested in Section (4) of the paper will satisfy the demand for instruction in broad principles, in administration and organization, in the kind of economic problems to which Mr. Dickinson specially refers, and in the ways in which the engineer must be prepared to deal with his fellows in all his relations with them. Obviously no more than a mere beginning of all this can be made in an academic place. Experience is the only certain instructor in the last details, but a little initial guidance will make the later learning easier by far than if the engineer came into contact with administrative problems quite unprepared. One thing that can scarcely be acquired at all in a college is skill in dealing with men: Mrs. Matthews, Mr. Fleming, and others have pointed out how essential it is to learn this from personal contact with those who are employed in works; and still others have reminded us that men do not act according to any formula. I mention these points once more because of their tremendous importance, and I suggest that if the engineer finds that the laws of man are painfully different in character from the laws of nature, there is all the more incentive in that for him to try to bridge the gulf and to improve the laws of man. Mr. Carr has rightly emphasized the intimate way in which we are bound up in our fortunes and misfortunes with many others, between whom and ourselves there is continual mutual dependence, and he has also shown how great a responsibility we may have for the welfare of others in times of distress. Let us be thankful for everything that convinces us afresh of the impossibility of one suffering without bringing hurt to all, or, on the other hand, of one advancing without bringing gain to all; and let us clearly realize the fallacy underlying any attempt to separate us and to make us stand alone or in sections and classes alleged to have opposing interests. Several people have remarked on industrial problems, and their hints of

possible solutions of some of them are welcome additions to the discussion. The subject must be left there so far as the present occasion is concerned, for, tempting as it is to discuss it further, its controversial aspect arises all too readily.

Mr. Anson refers to the conflicting opinions of experts. Are not these due to the impossibility that any one of us can possess complete knowledge and understanding of any problem? And if experts of equal eminence differ, does not that merely show the enormous complexity of the particular question before them? The final difficulty is how to find a comprehensive answer; that is, how to combine the partial answers of the several experts into a coherent whole. This is never easy, and usually it can only be done according to the special circumstances of each case; but it is at least certain, as Mr. Swinburne will doubtless particularly support me in saying, that to leave the settlement to the vote of electors or of their elected representatives is usually the way to ensure the kind of decision that might be equally logically obtained by putting all the possible answers, written on slips of paper, into a hat, by getting the first stranger who passed by to draw out one of them, and by adopting that as the true solution.

I want to emphasize once more the value of reading the works of great writers. A sense of the melody of rightly chosen words will add to the harmony of our whole life, and will increase the resources of our thought. What would not many of us give to be able to find words so apt as in this poem by A. Doris L. Wilson, printed recently in *The Poetry Review*?

EPITAPH.

All loveliness she sought.
Disgrace, despair
Struggled to dim the courage of her eyes,
And Poverty, seeing her spirit flame,
Bruised her with deadly pain
Till Death the Healer came.

* * * * *

And now she sleeps, her calm brave face,
Small chin, grave lips and eyes a long, long space
So still.
So still she lies
She cannot know this earth hath given
A sweeter bed to her beneath wide heaven,
She cannot know the rains will fill
Her folded hands and hair
With grass and cowslip fragrant there,
Nor can she hear
Increasing year by year
The brook that dusks and gleams past fern and firs.
Only long quietness and night are hers.

Prof. Stoney rightly says that extensions and progress come by extrapolation; but I do not think that that makes extrapolation less dangerous. All pioneering is extrapolation, and pioneers are taking risks all their lives. So long as the risks are recognized and understood, their power to hurt is lessened. But let us realize that they exist, and let us not complain too much if the larger machine, designed by extrapolation, does not turn out quite so good as was expected.

Dr. Ferranti's remarks about the need for persuading people to come to the help of the engineer who has something serviceable to propose to them and to carry out with their aid, are a useful comment on what I said about the results of an engineer's work being used for merely commercial ends. The emphasis in my sentence is on "merely," and the commercial exploitation of the work of engineers, in ways that probably they themselves never intended, would have been impossible had they been possessed of the qualities that would have allowed them to obtain help, as Dr. Ferranti suggests, and had they then been able themselves to develop their own work along the lines of their own desire. This leads us to recall once more the need for the cultivation of personality, and for the acquisition of the power of effective contact with other men.

I would particularly thank Mr. Bridges for having pointed out for me that the exceeding of mere duty is the lubricant that will ease the creaking of the mechanism; I am, indeed, specially grateful to him for all that he has contributed to the discussion. I hope that no one who sees this will fail to read what he has written on the subject of the second mile. It is action on that kind of principle that makes life a magnificent thing and prevents it from ever being a mere dreary routine of soul-destroying tasks. The more we appreciate the truth of this, the more shall we agree with Prof. Miles Walker when he points out that the service of humanity should be the main object of existence. There are some who give that they may receive, and there are others who receive that they may give. According to his nature is the thought of each man about his due and his duty; but in our inmost heart we know where blessedness lies.

I began by mentioning something said by Mr. Dunsheath. I find myself, as it happens, closing with a reference to another thing hinted at in his remarks: I mean the realization that change is the essence of life. Death itself, indeed, is but a passage to a new state, and cannot cut off the undying part of us from somehow sharing in all that is still to come.

Death! There is not any death, only infinite change;
Only a place of life which is novel and strange.
Change! There is nought but change and renewal of strife,
Which make up the infinite changes we sum up in life.
Life! What is life, that it ceases with ceasing of breath?
Death! What were life without change, but an infinite death?

As I lie on my bed, and the sun, like a furnace of fire,
Burns amid the old pines in the west, ere the last ray expire,
Can I dream he will rise no more, but a fathomless night
Shall brood o'er Creation for ever, and shut out the light?
It is done, this day of our life; but another shall rise,
Day for ever following day, in the infinite skies
Day following day for ever!

Day following day, with the starlit darkness between;
Or, maybe in a world where Dawn comes ere our Sunset has been,
Day following day for ever!

For ever! though who shall tell in what seeming or where?
In what far-off secret space of God's limitless air?

TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. EDWARDS, Associate Member.

(ABSTRACT *of Address delivered at* MIDDLESBROUGH, *23rd November*, 1925.)

ELECTRICITY SUPPLY.

It is the prerogative of a chairman to discourse on a variety of subjects, and the opportunity is often used to survey the progress made in the whole field of electrical engineering during the preceding year. This is invariably a fascinating subject, as each year is a record of astonishing progress, not only in this country but throughout the world. A few years ago the difficulty of electrical engineers was to interest the man in the street in the possibilities of electricity. This aim has now been realized to a large extent and people everywhere are awake to the benefits bestowed on the community by the unlimited use of electrical energy. It would appear that we are now on the flood tide of popularity and that during the next few years the use of electricity will increase by leaps and bounds. One has evidence of this if one compares the present financial standing of various supply undertakings with that of, say, three years ago. The shares of the leading London supply companies show a capital appreciation of approximately 50 per cent, with a corresponding increase in dividends. The provincial companies also show a substantial improvement in their financial position, which, considering the depression in trade generally, is very encouraging.

There appear to be three definite stages in the development of every new industry. We have seen them illustrated in the case of railways, telegraphy and electricity supply. First, there is the initial boom when people rush to invest in the new industry and numerous companies are floated, some of them sound and others the reverse. This initial boom is followed by an inevitable reaction, when only the companies formed on sound lines can survive and the failure of many of the weaker ones brings the whole industry into disrepute with the investing public. This phase in turn passes away and, if it is worthy of doing so, the industry will gradually regain its prestige and develop on a surer foundation. It is to be hoped that the electrical industry has now reached this stage and, provided it is not made the catspaw of political parties but is left untrammelled to work out its own salvation, I am confident that the next decade will see unprecedented developments.

Before I finish with the general aspect of electricity supply there are two directions in which development so far has been rather backward in this country. I refer to railway electrification and rural electrical supply. It seems to me that these two aspects are largely complementary. The countryside is covered in every direction with a network of railways, and few places are situated more than a dozen miles from a railway station. When these are electrified, does it not seem feasible that the electrical network which will follow the railway network shall be used to give a supply of electricity to hamlets and towns which otherwise could not be supplied economically? Incidentally, these local supply networks would help to carry the huge capital cost that railway electrification involves. Still, even under existing conditions, there is evidence of a new spirit in rural electrification. Small villages in various parts have their electric generating plant driven by water power, where available, or by oil engines. The equipment is often primitive and inefficient and the cost per unit high, up to a shilling in some places, but, even so, these small undertakings are a boon to village life.

Under such a scheme as I have suggested above, power would be available at economic rates all over the country. We might thus hope to see a revival of village industries and a gravitation of population from the congested city slums to the village greens.

ELECTRICITY IN STEELWORKS.

I do not propose to deal further with the general aspect of the electrical industry, although it would be of great interest to outline the developments in different directions during the past year. I propose to confine my further remarks to the applications of electricity which more particularly concern this district and which are presumably of greater interest to the members of this Sub-Centre.

Foremost among these applications is undoubtedly the use of electricity in iron- and steel-works. We have had able papers on this subject, but somehow I feel that engineers not actually engaged therein have not a true idea of its magnitude and importance. By the courtesy of some of our members I have been able to compare the generating systems at four typical local works and I find that the maximum load varies from 6 000 to 12 000 kW and that the units generated in one works alone exceeded 30 millions per annum. When it is remembered that there are eight or nine works of a similar capacity on Tees-side, members will understand what I mean. These works have large generating plants of their own, using some form of waste heat from metallurgical processes; they are generally self-contained systems with their high-tension transmission lines, transformer substations, switch-houses and distribution centres scattered about the works. These systems have generally grown from very small beginnings, and the process is one of evolution rather than revolution. In the works with which I am connected the first electrical plant was a Brush arc-lighting dynamo supplying about

40 arc lamps in series at 2 000 volts. Then followed a small high-speed reciprocating steam set supplying a few small two-phase motors at 250 volts. Other similar sets followed and later a mixed-pressure turbine was installed. During the war this peaceful evolution almost became revolution, and a high-pressure three-phase system was inaugurated, supplied from gas-engine-driven generators. To-day this system is quite up to date and all the electric power used in the works, besides a large amount transmitted to an allied works, is generated entirely from blast-furnace gas.

This instance is typical of many others and the process is by no means completed. As steam-driven plant becomes worn out and obsolete it is being displaced everywhere by electric drive. The automatic possibilities of the latter often lead to the displacement of the skilled attention which is necessary with steam drive, and the economies resulting from the change invariably show an excellent return on the capital expenditure involved.

As the electrical plant has gradually evolved from small beginnings, so has the responsibility for its maintenance increased. In the early days it was under the nominal control of the works engineer and was actually looked after by a wireman or electrician whose technical knowledge was generally limited. To-day the situation is quite changed and the electrical man has as much responsibility as, if not more than, the engineer of the average public supply undertaking. His responsibilities are certainly more varied, because he not only has charge of the generation and distribution of the electric power, but is also responsible for its utilization, with its manifold applications. The only part he is spared is the commercial responsibility, with its dealings, pleasant and otherwise, with the electricity committee on the one side and consumers on the other. On the other hand he is not free from financial responsibilities, especially at these times when capital expenditure has to be cut down to a minimum and working costs are scrutinized to the last penny. He is often discouraged by having a scheme, which promises an excellent return on the outlay, turned down because the capital expenditure involved is at these times prohibitive. It is encouraging, however, to find that the management of large works is recognizing more and more the possibilities of electricity and the vast economies that its adoption can secure. I think it was the late Andrew Carnegie who said that it was always a feast or a fast in the steel trade. When trade is booming it is impossible to shut down a plant for the length of time necessary for extensive alterations, and in times of depression, such as those through which we have lately been passing, there does not seem to be the necessary confidence in the future to tempt the directors of these companies to sanction heavy capital expenditure.

During and since the war several steel plants have been put down in this country on modern lines and are marvels of efficiency. Labour-saving has been considered throughout and electric drive is practically universal. They compare favourably with any works on the Continent or in America. Apart from these few instances the average iron- and steel-works is very out-of-date and, in my opinion, such works cannot hope to survive in the struggle for existence, which is more intense to-day than ever, unless they are prepared and able to remodel their plants on up-to-date principles, making use of every means to cheapen production and eliminate waste. If the estimated saving resulting from some new process be sufficient to repay the capital expenditure within a reasonable time, the scheme should be adopted, although it may mean the ruthless scrapping of plant which has by no means reached the end of its useful life. Only by such means can our steel industry hold its own, and in such a process electricity is bound to play a predominant part; and the time is approaching when the steelworks will become a "function of the electric motor."

Some two years ago I read an informal paper before this Sub-Centre, in which I tried to prove that if the so-called waste heat evolved in the conversion of iron ore to finished steel were properly utilized in the generation of electric power, theoretically not only would the power requirements of the works be satisfied but there would be a margin for use elsewhere. It must be understood that this balance will only hold good when the works are operating under ideal conditions. Actually these conditions vary continually, and while at times there will be a large surplus of power, at others the power demand will exceed the supply. In practice, therefore, it is essential that the power system of a fully electrified works be linked up with a separate source of power to make up the deficiencies and level up the load curve. The ideal arrangement is parallel running with a large public supply system such as we have in this district. By this means not only will the periodic shortages of power in the works be supplied, but an outlet will be obtained for the surplus energy which would be available at certain periods.

For such a scheme to be attractive an equitable charge must be arranged, not only for all energy supplied to the works, but also for the outgoing units. I feel that there is room for effective co-operation on these lines, with mutual advantage to both parties, not to speak of the resultant conservation of our national resources. Where this co-operation is for some reason not practicable, consideration might be given to other means of utilizing the surplus power available at certain periods. An instance of this would be some electrochemical process where large variations in the supply of energy would not be detrimental to the working of the process. What must be remedied is the loss of potential energy now going on at many of the iron- and steel-works.

I wish now to speak on a few points of practical interest to the steelworks engineer.

Large Gas Engines.

I am still convinced of the superiority of gas engines over steam turbines for use with blast-furnace gas. Over four years' experience with large gas engines has confirmed my faith in their reliability and efficiency.

Two gas-engine driven sets of 1 000 kW capacity have generated 47½ million units since the beginning of 1922 without a serious breakdown. During the last two years, since a routine of systematic cleaning has been adopted, there has been practically no interruption to supply. Although up to now I believe the largest

vertical gas engine built is of only 1 000 kW capacity, horizontal sets have been built up to 5 000 kW and one set of this size has recently been installed at Staveley. The thermal efficiency of an engine of this size will be about 28 per cent, which is much higher than any obtainable from steam-turbine plants.

As far as my experience goes, it is an advantage if the gas engines are run in parallel with a steam-turbine station, especially on a fluctuating load such as rolling-mill drives. The flywheel effect of the high-speed turbine is naturally much greater than that of the low-speed gas engine, and exercises a steadying effect on the load. I have never noticed "hunting" with gas engines when dealing alone with a load of this character, but the variation in speed and voltage becomes pronounced. The cost of lubrication of gas engines is fairly heavy, but this can be reduced by a proper system of oil filtration.

Alternating Current *v.* Direct Current.

I do not propose to-night to touch upon the vexed question of alternating current versus direct current for steelworks, except to mention that personally I have found the former satisfactory except for isolated duties such as magnets. Where the primary system is alternating current I do not consider that the advantages of the d.c. drive warrant the expense and complication of conversion. Where direct current is essential for exceptional duties it can be provided by small converting sets supplying merely the particular plant in question.

Transmission System.

The correct layout of the transmission and distribution system in a large works is a matter which needs very careful consideration. The future policy in the way of extensions is generally very nebulous and often a large demand is required at short notice. It is, therefore, wise policy to allow for a good margin over the immediate requirements and to make the distribution system as flexible as possible.

The primary transmission should be kept high; 6 000 or even 11 000 volts would be an economical voltage for a works covering a large area. If possible the sub-stations should be self-contained buildings properly designed for the purpose in hand, although too often an odd corner of an existing building is considered by the management to be sufficient for the purpose.

Duplication, wherever possible, is essential for that reliability which must obtain in steelworks, and it must never be forgotten that a certain proportion of the plant runs for many months without stoppage, even at holiday time. Duplication on the low-tension side is equally desirable, and I have found a system consisting of a number of ring mains the cheapest way to secure that end.

Power Factor of Steelworks.

The power factor of a steelworks is generally accepted as being very low, but it need not be as bad as it is painted. Steelworks engineers have to be very conservative in their outlook and provide motors with an ample margin of power for the work in hand. They also have a predilection for ample air-gaps and, in their opinion, maximum reliability is a greater merit in a motor than maximum efficiency and power factor. On many duties in a steelworks, such as cranes and roller drives, the motor has to be constantly reversed, sometimes up to 500 times an hour, and it is essential that the inertia of the moving parts be kept as low as possible, with the result that low-speed motors are favoured, with a further lowering of efficiency and power factor.

Whilst in full agreement with this policy I find that there are in most sections of the works certain constant running drives in favourable situations where a reasonably high-speed motor of high efficiency and power factor can be installed, and on certain heavy drives auto-synchronous machines can be used with advantage. By judicious management the power factor of most sections of the plant can be kept at, say, 75 per cent. In the case of the typical works load I mentioned earlier it varied between 0·7 and 0·75. Still, in some cases, further power-factor improvement is desirable and the installation of static condensers should be considered, particularly if extensions are under consideration, when their use can often effect a saving on mains and transformers greater than the cost of the condensers themselves.

Steelworks Motors.

I have mentioned the question of steelworks motors and this is a matter of sufficient importance to warrant further comment. Special types of d.c. motors for steelworks use have, of course, been manufactured for several years, and have given satisfaction, but it is only comparatively recently that their counterpart in a.c. machines has been brought out. I think that we owe their development to a great extent to a well-known local steelworks engineer, who has encouraged their manufacture for some years.

The latest development is a squirrel-cage rotor with high-resistance end connections which give satisfactory starting torque with a reasonable starting current. It is not necessary to enlarge on the advantages of this type of motor with its consequent simplification of control gear. For small sizes up to, say, 25 h.p. a simple stator reversing-switch is all that is necessary; for larger sizes reversing stator contactor-gear is advisable. Motors of this type are now being largely used for crane work, where the resultant freedom from complication of wiring is a great advantage. So far these motors have stood up well to the exacting steelworks conditions. When it is remembered that on slip-ring motors about 80 per cent of the breakdowns occur in the wound rotor it will be seen that the rugged squirrel-cage type should make for that reliability which is a *sine qua non* of steelworks requirements.

Whilst on the subject of motors I should like to mention a matter which has been discussed previously at Institution meetings. I refer to their standardization. It does seem to me that it is time some definite move was made in that direction and I would suggest that it is a suitable subject for the attention of the British Engineering Standards Association. I see the difficulties that stand in the way, but I think that it would be quite possible for the different manufacturers

to standardize certain dimensions which would make motors of the same rating interchangeable. It is not expedient that the purchaser should be bound to one particular make because he requires a motor to be a duplicate of one already in commission.

A feature of present-day motor design is the increasing popularity of ball and roller bearings, and certain makers are now fitting these exclusively on their standard machines. The doubts and suspicion with which their introduction was received by maintenance engineers have been largely dispelled.

I am glad to report an improvement in the conditions under which motors have to operate in steelworks. The old days of cast gears and overhung pinions are passing, and machine-cut gears and outboard bearings are standard practice in modern plants. In the lay-out of new schemes consideration is given to the facility of changing motors where necessary.

Electric Locomotion.

The question of electric locomotion in steelworks is one that has attracted attention for many years, but, as far as I know, electric traction has not been adopted for general use in any steelworks in this country.

At first sight the suggestion is very attractive and it would seem that large economies could be obtained from its adoption, as the steam locomotive in the average works is a very inefficient piece of apparatus. When one goes into the matter more deeply one finds difficulties almost insuperable at present. A network of overhead trolley lines is out of the question, as they would have to be erected at an absurd height to give the necessary clearance for the jib cranes which are continually moving about the works. The only possible solution is a battery locomotive, preferably in combination with overhead collectors for use on those particular tracks where they can be permitted. The better acquainted an electrical man becomes with the conditions under which the works locomotive has to operate, the more disinclined will he be to advise the management to experiment with a battery locomotive. There are certain duties, however, such as haulage of coke from ovens to blast furnaces, or slag from furnaces to slag tip, where an overhead system might be feasible and where electric traction is well worth consideration.

Electrical Staff.

Finally, a word as to the electrical staff. They must be taught that safety in operation is a first requirement, and suitable rules and regulations for the proper operation of the plant must be strictly enforced if this is to be secured. They must learn that the proper earthing of apparatus is as important as the proper connection to the line. They should be encouraged to take an intelligent interest in the working of the plant and to obtain the technical knowledge which will enable them to acquire that interest. Only by such means can the *esprit de corps* be gained which is necessary to get the maximum efficiency out of the plant.

In conclusion I would congratulate my fellow members that we are engaged in a profession that offers such boundless opportunities for our powers. Our young men may see visions and our old men may dream dreams, but none can foretell the future of the electrical industry. Certain it is that it is at present, if not in its infancy, at any rate in its strong and vigorous youth. As yet there is no sign of a halt in its triumphant progress, and I feel that its past triumphs will sink to insignificance compared with those the future holds in store.

PROBLEMS IN CONNECTION WITH TWO PARALLEL ELECTRIFIED CYLINDRICAL CONDUCTORS.*

By ALEXANDER RUSSELL, M.A., D.Sc., LL.D., F.R.S., Past President.

(*Paper first received* 19*th May, and in final form* 7*th October,* 1925.)

SUMMARY.

Electrostatic problems in connection with two unequal parallel cylinders, and with single-core cables when the axes of the cores are parallel but not coincident with the axes of the outer cylinders, are considered. The solutions are given by formulæ the numerical value of which can be readily evaluated. Novel relations are given connecting the capacity between any two cylinders with the capacities between two equal cylinders and with the capacities of cylindrical condensers.

When there are two parallel cylindrical conductors with an alternating difference of potential maintained between them, it is well known that electric currents flow in them. The magnitude of these currents can be computed in certain cases and are found to be in agreement with their observed values. It is also known that when we have two equal conductors and the dielectric between them is a gas at a known temperature and pressure, then the corona or the sparking potential can be computed when we know the value of the maximum potential gradient between them. In addition, the electrostatic force between the conductors can be computed in certain cases.

In treatises on electrostatic theory it is generally considered sufficient to give the capacity formulæ for two equal parallel conductors and for a concentric main. One or two give the formulæ for the forces between the cylinders and for the maximum potential gradient in the dielectric of a concentric main, but practically none state clearly the limitations of the formulæ they give. It has seemed to the author, therefore, that it would be useful to point out the limitations in the ordinary theory owing to the assumptions made, and to give a résumé of the ordinary mathematical formulæ. It is shown that in many cases the solution of problems when the cylinders are unequal in size, or when the axis of the core is not concentric with the axis of the sheath, can be written down at once from the ordinary formulæ for equal cylinders and concentric mains.

THE CAPACITIES OF CYLINDERS.

We first of all suppose that the cylinders are of infinite length, so that the field surrounding them is not disturbed by the irregular electrical distribution at their ends. We suppose that the charges per unit length of each cylinder are equal in magnitude and of opposite sign. These assumptions greatly simplify the problem, as the equipotential surfaces are all cylindrical and all cut another set of cylinders orthogonally. Finally, it is customary to define the capacity per unit length between the two cylinders as the ratio of the positive charge per unit length to the difference of potential between the cylinders. The reason for adopting this definition is, doubtless, that it is a quantity readily measured in practice. It seems to the author that it would be helpful in practice to call the ratio of the charge per unit length on one of the cylinders to its potential the "capacity" of that cylinder, or, if it is preferred, the "capacity of that cylinder in the presence of the other cylinder." This quantity can be calculated quite as easily as the capacity between the cylinders, and a knowledge of its value is instructive.

The assumption that the electric charges on the two cylinders are equal and opposite is a serious one. This is not always true in practice, and it is highly desirable that simple formulæ should be found by means of which the capacities, the maximum potential gradient, and the forces, could be computed in the general case. Maxwell showed that if (q_1, v_1) and (q_2, v_2) be the charges per unit length and the potentials of the two cylinders, then

$$q_1 = k_{11}v_1 + k_{12}v_2, \quad \text{and} \quad q_2 = k_{22}v_2 + k_{12}v_1 \quad . \ (1)$$

where k_{11}, k_{22} and k_{12} are constants which depend on the radii of the cylinders, their distance apart and the inductivity of the medium between them. These constants are called the "capacity coefficients," and if their algebraical values could be readily found we should have practically the complete solution of the problem. So far as the author knows, no formulæ that would be useful from the engineering point of view have yet been given for them. In this paper we practically consider only the case when the charges on the two cylinders are equal and opposite.

Some of the formulæ given below have been published before, but the methods of obtaining them have been simplified. Novel relations connecting the capacities of cylindrical condensers with the capacities of other cylindrical condensers and with the capacities of parallel cylinders are also given.

THE PROBLEM OF TWO ELECTRIFIED CYLINDRICAL CONDUCTORS.

Let us first consider the case of two parallel cylindrical conductors external to one another. Let their circular sections be as shown in Fig. 1. Let C be the centre of the circular section whose radius is a, and D be the centre of the circle whose radius is b. We shall denote the distance CD between the axes of the cylinders by c. Now it is known by geometry that two points A and B

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(the inverse points) can be found such that CA . CB $= a^2$ and DB . DA $= b^2$. It is easy to show that the circle described on AB as diameter will cut the two circles orthogonally. Thus if r be its radius, we have

$$c = \sqrt{(a^2 + r^2)} + \sqrt{(b^2 + r^2)}.$$

Hence $$cr = 2\{s(s-a)(s-b)(c-s)\}^{\frac{1}{2}} \quad . \quad . \quad (2)$$

where $$2s = a + b + c.$$

By logarithms, the value of r can be calculated very readily from (2) in every case.

It is found useful to introduce two new quantities α and β, which are defined by the equations

$$\sinh \alpha = r/a \quad \text{and} \quad \sinh \beta = r/b \quad . \quad . \quad (3)$$

Hence $$cr = ab \sinh(\alpha + \beta) = ab \sinh \omega \quad . \quad . \quad (4)$$

if we denote $(\alpha + \beta)$ by ω. It also follows that

$$\cosh \omega = \frac{c^2 - a^2 - b^2}{2ab} \quad . \quad . \quad . \quad . \quad (5)$$

and CA $= a\epsilon^{-\alpha}$, CB $= a\epsilon^{\alpha}$, DB $= b\epsilon^{-\beta}$ and DA $= b\epsilon^{\beta}$

Let us now suppose that the charge on the cylinder whose centre is C is q per unit length, and that the charge

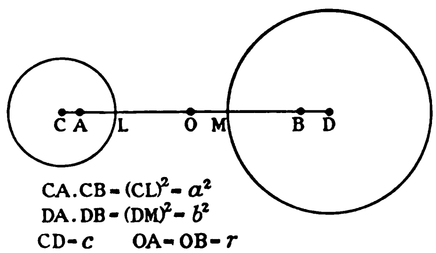


FIG. 1.

on the other cylinder is $-q$ per unit length. Then if v be the potential * at any point P between them, we have, assuming the medium to be a vacuum,

$$v = 2q \log(\mathrm{BP}/\mathrm{AP}) \quad . \quad . \quad . \quad . \quad (6)$$

It is well known that the locus of a point P which moves so that BP/AP is a constant is a circle. Thus the equipotential surfaces are cylinders surrounding A and B respectively.

If P is a point on the cylinder whose centre is C and if v_1 be its potential, we have

$$v_1 = 2q \log\left(\frac{\mathrm{BP}}{\mathrm{AP}}\right) = 2q \log\left(\frac{\mathrm{BL}}{\mathrm{AL}}\right) = 2q \log \frac{a\epsilon^{\alpha} - a}{a - a\epsilon^{-\alpha}} = 2q\alpha$$

Thus $$\frac{q}{v_1} = \frac{1}{2\alpha} \quad \text{and similarly} \quad \frac{-q}{v_2} = \frac{1}{2\beta} \quad . \quad . \quad (7)$$

These ratios are the capacities of the two cylinders in the presence of one another. We shall denote these capacities by $C_a(a, b, c)$ and $C_b(a, b, c)$.

The capacity $C(a, b, c)$ between the two conductors is given by

$$C(a, b, c) = \frac{q}{v_1 - v_2} = \frac{1}{2(\alpha + \beta)} = \frac{1}{2\omega}$$
$$= \frac{C_a(a, b, c) \cdot C_b(a, b, c)}{C_a(a, b, c) + C_b(a, b, c)} \quad . \quad (8)$$

* A. RUSSELL: "Alternating Currents," vol. 1, p. 163.

When engineers refer to "capacity" they usually mean the ratio which we denote by $C(a, b, c)$.

It is interesting to notice that

$$C_a(a, b, c) = \frac{1}{2\alpha} = \frac{1}{2 \log(a/\mathrm{CA})}$$

and $$C_b(a, b, c) = \frac{1}{2 \log(b/\mathrm{BD})} \quad . \quad (9)$$

Hence $C_a(a, b, c)$ is the capacity per unit length of the concentric main whose outer radius is a and inner radius CA. Similarly we have

$$C(a, b, c) = \frac{C_a(a, b, c) \cdot C_b(a, b, c)}{C_a(a, b, c) + C_b(a, b, c)} = \frac{1}{2 \log\{ab/(\mathrm{CA} \cdot \mathrm{BD})\}}$$

We also have

$$C(a, b, c) = \frac{1}{2\omega} = \frac{1}{2 \log_{\epsilon} m} \quad . \quad . \quad . \quad (10)$$

where $$m = \frac{d}{2} + \sqrt{\left(\frac{d^2}{4} - 1\right)}$$

and $$d = \frac{c^2 - a^2 - b^2}{ab}$$

THE ELECTRIC FORCE BETWEEN THE CYLINDERS.

The energy stored in the field

$$= \tfrac{1}{2}C(v_1 - v_2)^2 = q^2/(2C) = q^2\omega$$

where C stands for $C(a, b, c)$.

Hence if F be the force between the cylinders

$$F = \frac{\partial}{\partial c}(q^2\omega) = q^2\frac{\partial \omega}{\partial c}$$

Now by (5), $\sinh \omega \dfrac{\partial \omega}{\partial c} = \dfrac{c}{ab}$, and thus by (4), $\dfrac{\partial \omega}{\partial c} = \dfrac{1}{r}$.

We thus get the interesting theorem that

$$F = q^2/r \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

It follows that, when the charges on the cylinders are equal and opposite, the attractive force between them varies inversely as the radius r of the smallest cylinder which cuts them both at right angles. This is true whether the cylinders are external to each other or one is internal to the other. The value of r for a given pair of cylinders is easily computed from (2). In (11), F is in dynes, q is in electrostatic units, and r is in centimetres. (A coulomb equals 3×10^9 electrostatic units.)

THE MAXIMUM POTENTIAL GRADIENT BETWEEN THE CYLINDERS.

It is well known that the electric field between the cylinders (Fig. 1) is the same as that produced by two electrified wires cutting the paper perpendicularly at A and B respectively and having charges $+q$ and $-q$ per unit length. The potential gradient (electric force) between the cylinders will have its greatest numerical values at the points L and M where the line joining the centres of the two circular sections intersects

them. If we denote the potential gradient at L (Fig. 1) by R_L, we have

$$R_L = \frac{2q}{\mathrm{AL}} + \frac{2q}{\mathrm{BL}} = \frac{2q}{r}(1 + \cosh \alpha) \quad . \quad . \quad (12)$$

Similarly $$R_M = \frac{2q}{\mathrm{BM}} + \frac{2q}{\mathrm{AM}} = \frac{2q}{r}(1 + \cosh \beta) \quad . \quad (13)$$

It follows that if a is less than b, R_L is greater than R_M.

We would naturally expect that the sparking potential between the cylinders in a gas would be determined by the value of R_L. When the radius of each of the cylinders is a it is known that the spark takes place or the corona occurs when R_L is given by a formula of the type

$$R_L = \mathrm{A} + B/\sqrt{a} \quad . \quad . \quad . \quad . \quad (14)$$

where A and B are constants. It would be very interesting to know whether (14) applies when the cylinders are unequal. A research to determine this would be of considerable theoretical value.

From (12) we get

$$R_L = \frac{2q}{r}\left\{\frac{(c + a)^2 - b^2}{2ca}\right\} = \frac{2q}{a}\sqrt{\left[\frac{s(s - b)}{(s - a)(c - s)}\right]} \quad (15)$$

Similarly $$-R_M = \frac{2q}{b}\sqrt{\left[\frac{s(s - a)}{(s - b)(c - s)}\right]} \quad . \quad . \quad (16)$$

Since $q = C(a, b, c)\,(v_1 - v_2)$, see (10), we have

$$q = \frac{v_1 - v_2}{2 \log_e m} \quad . \quad . \quad . \quad . \quad (17)$$

where $$m = \frac{d}{2} + \sqrt{(\tfrac{1}{4}d^2 - 1)}$$

and $$d = \frac{c^2 - a^2 - b^2}{ab}.$$

Thus R_L can be found from (15) and (17) when the difference of potential $(v_1 - v_2)$ is known, provided that the charges on the cylinders are equal and opposite.

If we denote LM by x, and if x be not great compared with a or b, we have

$$R_L = \frac{v_1 - v_2}{x}\left\{1 + \frac{2b - a}{6ab}x\right\} \quad . \quad . \quad (18)$$

approximately. When the cylinders are equal

$$R_L = \frac{v_1 - v_2}{x}\left\{1 + \frac{x}{6a} - \frac{x^2}{180a^2} + \frac{43x^3}{55\,296a^3}\right\} \quad (19)$$

approximately.

For instance, when $x = a$,

$$R_L = \frac{v_1 - v_2}{x} \times 1{\cdot}1618$$

The true value of the multiplying factor is $1{\cdot}1617$. It will be seen that provided x is not greater than a, formula (19) can be used for all practical purposes. When $x = 2a$, the factor given by (19) is $1{\cdot}319$ instead of $1{\cdot}315$.

Cylindrical Condenser.

Let the sections of the cylinders perpendicular to their parallel axes be as given in Fig. 2.

Then if A and B be the inverse points, we have $\mathrm{CA}\,.\,\mathrm{CB} = a^2$, $\mathrm{DA}\,.\,\mathrm{DB} = b^2$, and, if c be the distance DC between their centres, b must be greater than $a + c$. A circle described on AB as diameter cuts both circles orthogonally.

Let $\quad \mathrm{AB} = 2r = 2a \sinh \alpha_1 = 2b \sinh \beta_1$.

Then $\quad c = \sqrt{(b^2 + r^2)} - \sqrt{(a^2 + r^2)}$,

and thus $$cr = 2\sqrt{[s(s - a)(s - c)(b - s)]} \quad . \quad . \quad (20)$$

where $\quad 2s = a + b + c$.

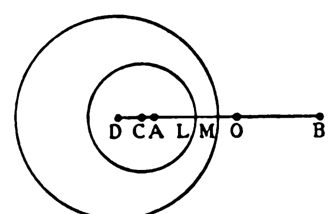
It readily follows (*l.c. ante*) that

$$v_1 = 2q\alpha_1 \quad \text{and} \quad v_2 = 2q\beta_1. \quad . \quad . \quad (21)$$

Hence $$\frac{q}{v_1 - v_2} = \frac{1}{2(\alpha_1 - \beta_1)} = \frac{1}{2\omega_1} = K(a, b, c)$$

where $$2 \cosh \omega_1 = \frac{a^2 + b^2 - c^2}{ab} = d \quad . \quad . \quad (22)$$

and $K(a, b, c)$ is the capacity per unit length of a cylindrical condenser whose inner radius is a, and outer



$\mathrm{CA}\,.\,\mathrm{CB} = (\mathrm{CL})^2 = a^2 \quad \mathrm{DA}\,.\,\mathrm{DB} = (\mathrm{DM})^2 = b^2$

$\mathrm{DC} = c \quad \mathrm{OA} = \mathrm{OB} = r$

Fig. 2.

radius b, and c is the distance between the axes of the cylinders.

Thus $$K(a, b, c) = \frac{1}{2 \log_e m_1} \quad . \quad . \quad . \quad (23)$$

where $m_1 = \frac{1}{2}d + \sqrt{(\frac{1}{4}d^2 - 1)}$ and d is given by (22).

Proceeding as before, we find that the attractive force F between the cylinders is given by

$$F = q^2/r \quad . \quad . \quad . \quad . \quad . \quad (24)$$

and that $$R_L = (2q/r)(1 + \cosh \alpha_1) \quad . \quad . \quad . \quad (25)$$

and $$R_M = (2q/r)(1 + \cosh \beta_1) \quad . \quad . \quad . \quad (26)$$

We also have $$\frac{q}{v_1} = \frac{1}{2 \log (a/\mathrm{CA})} \quad . \quad . \quad . \quad . \quad (27)$$

In these formulæ $$\cosh \alpha_1 = \frac{b^2 - a^2 - c^2}{2ac} \quad . \quad . \quad (28)$$

and $$\cosh \beta_1 = \frac{b^2 + c^2 - a^2}{2bc} \quad . \quad . \quad (29)$$

When x is small, we have

$$R_L = \frac{v_1 - v_2}{x}\left\{1 + \frac{2b + a}{6ab}x\right\} \quad . \quad . \quad (30)$$

approximately.

CAPACITY COEFFICIENTS FOR EXTERNAL CYLINDERS.

From (1) and (7) it follows that, whatever the charges on the cylinders are, we have

$$k_{11} = \frac{1}{2\alpha} + \frac{\beta}{\alpha}k_{12} \quad \text{and} \quad k_{22} = \frac{1}{2\beta} + \frac{\alpha}{\beta}k_{12} \,. \quad (31)$$

The problem of finding the three capacity coefficients of the two cylinders is thus reduced to that of finding a capacity coefficient of one of them.

In all cases we have

$$v_1 - v_2 = (q_1 + q_2)(\alpha - \beta) + (q_1 - q_2)(\alpha + \beta) \,. \quad (32)$$

For instance, when $q_1 = q_2 = q$, we have

$$\frac{q}{v_1 - v_2} = \frac{1}{2(\alpha - \beta)} \quad . \quad . \quad . \quad . \quad (33)$$

which can be readily computed.

Similarly when $q_2 = 0$,

$$\frac{q_1}{v_1 - v_2} = \frac{1}{2\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

THE INDUCTIVITY OF THE MEDIUM.

If the inductivity (specific inductive capacity) of the medium in which the cylinders are immersed be λ, then the formulæ given above for the capacities have to be multiplied by λ. The formulæ for the electric force between the cylinders have to be divided by λ, and the formulæ for the potential gradient are unaffected.

CAPACITY RELATIONS BETWEEN CYLINDRICAL CONDUCTORS.

The formulæ given above enable us to write down many simple relations connecting the capacities of external cylinders with each other and with the capacities of cylindrical condensers. These relations are instructive and interesting. They are also useful in practice as, in many cases, they enable the capacities to be computed more readily.

From formulæ (10) and (23) we see that the capacities C and K only depend on the ratios of a, b and c. Hence, if p be any number, we have

$$C(a, b, c) = C(pa, pb, pc) \quad \text{and} \quad K(a, b, c) = K(pa, pb, pc) \quad . \quad (35)$$

Thus, for external cylinders,

$$\begin{aligned} C(a, b, c) &= C\left(\frac{r}{\sinh\alpha}, \frac{r}{\sinh\beta}, \frac{r\sinh\omega}{\sinh\alpha\sinh\beta}\right) \\ &= C\{\sinh(\omega - \alpha), \sinh\alpha, \sinh\omega\} \\ &= \frac{1}{2\omega} = \frac{n}{2n\omega} \\ &= nC\{\sinh(n\omega - \alpha), \sinh\alpha, \sinh n\omega\} \quad (36) \end{aligned}$$

where n is any number.

Similarly, we find that

$$\begin{aligned} K(a, b, c) &= mK\{\sinh(m\omega_1 + \beta), \sinh\beta, \sinh m\omega_1\} \\ &= \frac{1}{2\omega_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37) \end{aligned}$$

Hence for all values of m, n, α, β and ω, we have

$$\begin{aligned} &nC\{\sinh(n\omega - \alpha), \sinh\alpha, \sinh n\omega\} \\ &\quad = mK\{\sinh(m\omega + \beta), \sinh\beta, \sinh m\omega\} \\ &\quad = \frac{1}{2\omega} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (38) \end{aligned}$$

This is a very general formula.

The following particular cases of (38) are useful :—

$$\begin{aligned} C(a, b, c) &= C[1, 1, \sqrt{\{c^2 - (a - b)^2\}}/\sqrt{(ab)}] \\ &= K\{(c^2 - a^2 - b^2)/ab, 1, 1\} \quad (39) \end{aligned}$$

and

$$\begin{aligned} K(a, b, c) &= K\{(a^2 + b^2 - c^2)/ab, 1, 1\} \\ &= C[1, 1, \sqrt{\{(a + b)^2 - c^2\}}/\sqrt{(ab)}] \quad (40) \end{aligned}$$

The formulæ (39) and (40) enable us to convert at once the problem of computing the capacity between any external or internal cylinders into the simpler one of finding the capacity between two equal cylinders.

We also have

$$\begin{aligned} C(1, 1, d) &= \tfrac{1}{2}K(d, 1, 1,) = \tfrac{1}{2}C[1, 1, \sqrt{(d + 2)}] \\ &= \tfrac{1}{2}C[a, b, \sqrt{(a^2 + b^2 + dab)}] \quad . \quad (41) \end{aligned}$$

where a and b can have any values.

For example, if we put $d = 142, a = 10$ and $b = 1$, we get at once

$$C(1, 1, 142) = \tfrac{1}{2}C(1, 1, 12) = \tfrac{1}{2}C(10, 1, 39)$$

For all values of c less than $a - b$, we find that

$$K(a, b, c) = C\{a, b, \sqrt{[2(a^2 + b^2) - c^2]}\} \quad . \quad (42)$$

and for all values of c between $a + b$ and $\{2(a^2 + b^2)\}^{\frac{1}{2}}$, we have

$$C(a, b, c) = K\{a, b, \sqrt{[2(a^2 + b^2) - c^2]}\} \quad . \quad (43)$$

For all values of m

$$C(a, b, c) = C\{ma, b/m, \sqrt{[c^2 - (a+b)^2 + (ma+b/m)^2]}\} \quad (44)$$

and

$$K(a, b, c) = K\{ma, b/m, \sqrt{[c^2 - (a+b)^2 + (ma+b/m)^2]}\} \quad (45)$$

It is also easy to show that

$$\begin{aligned} K(a, b, o) &= nK\left\{\frac{a^n}{b^n} + \frac{b^n}{a^n}, 1, 1\right\} = 2mC\left\{1, 1, \frac{a^m}{b^m} + \frac{b^m}{a^m}\right\} \\ &= C\{a, b, \sqrt{[2(a^2 + b^2)]}\} = 1/\{2\log(a/b)\} \quad (46) \end{aligned}$$

For example,

$$\begin{aligned} C(70, 10, 100) = K(70, 10, 0) &= 1/(2\log 7) \\ &= 0 \cdot 2569924 \ldots \end{aligned}$$

Dividing this number by 900 000 we get the value of $C(70,10,100)$ and of $C(7,1,10)$, in microfarads.

In general, we have

$$\begin{aligned} &K(a, b, c) \\ &= K(d, 1, 1) = K(d^2 - 1, d, 1) = K(d^3 - 2d, d^2 - 1, 1) = \ldots \\ &= 2K(d^2 - 2, 1, 1) = 3K(d^3 - 3d, 1, 1) = \ldots \\ &= 2K(d^2 - 1, 1, d) = nK(m^n, 1, 0) = 1/(2\log m) \,. \quad . \quad (47) \end{aligned}$$

where $d = (a^2 + b^2 - c^2)/ab$ and $m = \frac{1}{2}d + \sqrt{(\frac{1}{4}d^2 - 1)}$

Theorems similar to (47) in connection with $C(a, b, c)$ can be readily written down.

If we put $d = 2 + x$ in (41) we get

$$K(2 + x, 1, 1) = 2C(1, 1, 2 + x)$$
$$= \frac{1}{4 \log \{\frac{1}{2}\sqrt{x} + \sqrt{(1 + \frac{1}{4}x)}\}} = \frac{1}{4 \sinh^{-1}\sqrt{x}} \quad . \quad (48)$$

When x is not greater than unity we can use the formula

$$K(2 + x, 1, 1) = 2C(1, 1, 2 + x)$$
$$= \frac{1}{2\sqrt{x}}\left\{1 + \frac{x}{24} - \frac{17x^2}{5\,760} + \frac{137x^3}{276\,480} - \ldots\right\} \quad (49)$$

For instance, using this formula and (41), we get

$K(2\cdot 01, 1, 1) = 2C(1, 1, 2\cdot 01) = 5\cdot 002082 \ldots$
$K(2\cdot 5, 1, 1) = 2C(1, 1, 2\cdot 5) = 0\cdot 72136 \ldots (0\cdot 72135)$
$K(3, 1, 1) = 2C(1, 1, 3) = 0\cdot 5196 \ldots (0\cdot 5195 \ldots)$

The true values are given in brackets.

When $x/(a + b)$ is small, we have approximately

$$C(a, b, a+b+x) = \sqrt{\left[\frac{ab}{8(a+b)x}\right]}\left\{1 + \frac{a^2+b^2-ab}{12ab(a+b)}x\right\} \quad (50)$$

and

$$K(a, b, a-b-x) = \sqrt{\left[\frac{ab}{8(a-b)x}\right]}\left\{1 + \frac{a^2+b^2+ab}{12ab(a-b)}x\right\} \quad (51)$$

For example,

$C(98, 10\cdot 8, 109) = 2\cdot 4688 \ldots$
and $K(109, 98, 10\cdot 8) = 24\cdot 748 \ldots$

Denoting, as before, the capacity of the a cylinder in the presence of the b cylinder by $C_a(a, b, c)$, we have

$$C_a(a, b, c) = K(c, a, b). \quad . \quad . \quad . \quad (52)$$

For example,

$$C_a(1, 7, 10) = K(10, 1, 7) = \frac{1}{2\omega_1}$$

where $\cosh \omega_1 = \dfrac{10^2 + 1^2 - 7^2}{20} = \dfrac{26}{10} = \frac{1}{2}(5 + \frac{1}{5})$

Thus $\omega_1 = \log 5$, and therefore

$C_a(1, 7, 10) = 1/(2 \log 5) \quad = 0\cdot 3106674 \ldots$
$C_a(7, 1, 10) = 1/(2 \log 1\cdot 4) = 1\cdot 4860013 \ldots$
and $C\ (1, 7, 10) = 1/(2 \log 7) \quad = 0\cdot 2569924 \ldots$

To find the capacities in microfarads, we divide these numbers by 900 000. Notice that all the logarithms given in this paper are to the base ϵ. To convert common into Napierian logarithms we multiply by 2·3025851.

High Frequency Self-Inductance.

If $L_e(a, b, c)$ denote the high-frequency self-inductance per unit length of two external parallel cylinders, then *

$$L_e(a, b, c) = 2\omega = 1/C(a, b, c) \quad . \quad . \quad (53)$$

and if one cylinder surrounds the other,

$$L_i(a, b, c) = 2\omega = 1/K(a, b, c) \quad . \quad . \quad (54)$$

Hence we can write down theorems similar to those connecting the electrostatic capacities of the cylinders.

* *Proceedings of the Physical Society of London*, 1918-19, vol. 31, p. 126.

CIRCUIT CONSTANTS IN TRANSMISSION-LINE CALCULATIONS.*

By A. C. A. CALDWELL, B.E., Associate Member.

(*Paper first received 2nd October, 1924, and in final form 10th December, 1925.*)

SUMMARY.

In this paper the use of "circuit constants" for the calculation of transmission-line problems is dealt with in an elementary way, in the hope that many who perhaps would not have the time or patience to follow the original papers of Messrs. Evans and Sels may be encouraged to use their very powerful and useful methods.

To avoid having to refer to textbooks for the elements of complex algebra, a few notes on its use have been included.

The formulæ for calculating the constants of series and parallel circuits are developed; and the determination of the particular values of the constants for transmission lines, and for transformers, is dealt with in detail.

Following this, methods for dealing with more complex cases of lines supplying more than one substation, and branching lines, are dealt with. An actual example of an existing transmission line is worked out in detail.

INTRODUCTION.

For the purpose of calculating the performance of long-distance high-voltage transmission lines and networks, it is essential that capacity effects and the effects due to step-up and step-down transformers be taken into account. Hitherto it has been usual to calculate the characteristics of a transmission line with considerable pains and then to treat the transformers separately and more or less approximately, though their effects may easily be of the same order of magnitude as those produced by the line itself.

Again, it has been suggested that the transformer resistance and reactance may be added directly to the line resistance and reactance. This method also lacks accuracy, especially when high voltage and long distance make it imperative that the charging currents of both the line and the transformer be taken into account. To be able to take full and accurate account of both the line and transformers is therefore most desirable. That this may be done without undue labour and complication has been shown by Messrs. R. D. Evans and H. K. Sels in two papers on "Transmission Line Circuit Constants" and "Transmission Lines and Transformers." † While indicating the general method and stating the general formulæ necessary, the reader is left by these authors with very little in the nature of concrete example or instructions for applying the method to everyday uses. The method is, however, of very great practical value, and the following notes are an attempt to elaborate the practical details arising when the method is applied to simple and also to more complex cases in actual practice. The author has found the methods as developed herein of great service in predetermining voltage variations on the large power schemes now under development by the Public Works Department of New Zealand, particularly in connection with the Mangahao, Arapuni and Lake Coleridge transmission systems.

The use of circuit constants in transmission-line calculations is well known * and widely used, and it is by making use of these and similar constants for the transformers that any ordinary combination of lines and transformers may be treated as a whole and exact solutions obtained for any condition of loading.

USE OF COMPLEX NUMBERS.

Throughout these calculations complex numbers and complex algebra are used, and a few words covering the ordinary operations that will be continually employed may not be out of place.

Two methods of notation are in use and both have their special applications, and the elementary rules for the manipulation of both forms must be thoroughly mastered.

Assuming some vector of reference, a vector may be defined with respect to it :—

(1) By means of its projection on and at right angles to the vector of reference, the usual notation for a vector of length $\sqrt{(a^2 + b^2)}$ being $a + jb$, where a denotes the length of its projection on the axis of reference and b the length of its projection on an axis at right angles to the first, where j is an operator denoting a rotation of 90° in an anti-clockwise direction and is defined as $\sqrt{(-1)}$; j^2 therefore has the value "-1" and denotes a rotation through 180°.

(2) By means of its length and the angle between it and the vector of reference, the usual notation being of the form $r\underline{/\theta}$, where r denotes the length of the vector and θ the angle between it and the vector of reference, the symbol $\underline{/\theta}$ generally denoting a rotation through an angle θ in an anti-clockwise direction from the vector of reference, and $\overline{\backslash\theta}$ denoting a rotation in a clockwise direction. The vector of reference is generally taken as the positive direction of the ordinary x axis, so that $(a + jb)$ and $r\underline{/\frac{\pi}{4}}$ denote vectors in the first quadrant, while $(a - jb)$ and $r\overline{\backslash\frac{\pi}{4}}$ denote vectors in the fourth quadrant.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Electric Journal*, 1921, vol. 18, pp. 306 and 356.

* F. E. PERNOT: "Electrical Phenomena in Parallel Conductors"; J. L. LA COUR and O. S. BRAGSTAD: "Theory and Calculation of Electric Currents."

The following equations define the operations that will be used in this work.

Addition.—$(a + jb) + (c + jd) = (a + c) + j(b + d)$.
Subtraction.—$(a + jb) - (c + jd) = (a - c) + j(b - d)$.
Multiplication.—$(a + jb)(c + jd) = ac + jad + jbc - bd = (ac - bd) + j(ad + bc)$

$$r\underline{/\theta} \times s\underline{/\phi} = rs\underline{/\theta + \phi}$$

Division.—
$$\frac{a + jb}{c + jd} = \frac{(a + jb)(c - jd)^*}{(c + jd)(c - jd)} = \frac{(ac + bd) + j(bc - ad)}{c^2 + d^2} = \frac{ac + bd}{c^2 + d^2} + j\frac{bc - ad}{c^2 + d^2}$$

$$r\underline{/\theta} \div s\underline{/\phi} = (r/s)\underline{/\theta - \phi}$$

Involution.—$(a + jb)^2 = a^2 - b^2 + j2ab$

$$(r\underline{/\theta})^2 = r^2\underline{/2\theta}$$

Evolution.—$\sqrt{(r\underline{/\theta})} = \sqrt{(r)}\underline{/\tfrac{1}{2}\theta}$.

From the above it will be seen that in addition and subtraction it is convenient to use the j notation, while for multiplication, division, involution and evolution it is simpler to use the $r\underline{/\theta}$ notation. Where both multiplication and addition are concerned, however, it is often advisable to retain the j notation throughout and perform the four multiplications necessary for every product of two complex numbers, rather than change to the other notation involving the use of logarithms and tables of trigonometrical functions. This is especially true when a calculating machine is available.

For a fuller discussion of the algebra of complex quantities the reader should see Steinmetz's "Engineering Mathematics."

Circuit Constants.

Coming now to the use of the circuit constants, these may be defined by the general equations of an electric circuit :—

$$E_s = AE_r + BI_r \quad . \quad . \quad . \quad . \quad . \quad (1)$$
$$I_s = CE_r + DI_r \quad . \quad . \quad . \quad . \quad (2)$$

where E_s, I_s are the voltage and current at the sending end, E_r, I_r the voltage and current at the receiving end of the circuit and A, B, C, D the four constants of the circuit, the values of which for different types of circuits are derived below.

The significance of these constants may be visualized thus :—

Putting I_r equal to zero in Equation (1), i.e. the circuit excited but without load, A gives the ratio of E_s to E_r; it is unity for short lines and less than unity for long lines. B is the impedance of the circuit as modified to allow for distributed capacity and reactance, and BI_r gives the impedance drop due to the load.

Putting I_r equal to zero in Equation (2), CE_r gives the capacity current on open circuit. DI_r denotes the load current at the sending end as modified by traversing the line.

* $(c - jd)$ is termed the conjugate of $(c + jd)$.

The above equations may also be stated in the following form to express the receiving-end conditions in terms of the sending-end conditions.

$$E_r = DE_s - BI_s \quad . \quad . \quad . \quad . \quad . \quad (1a)$$
$$I_r = - CE_s + AI_s \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

As previously stated, the first aim of this method of treatment is to reduce the circuit or network to an equivalent simple circuit with one set of constants embracing the whole of the individual lines, transformers, etc.

The necessary equations for determining the general constants of circuits in series and parallel are derived as follows :—

Let the voltages, currents, and constants of three circuits in series be as shown in Fig. 1, where the

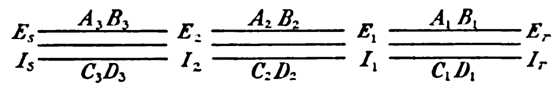


Fig. 1.

separate circuits will generally be either sections of transmission lines with dissimilar characteristics, or sections of transmission lines and transformers.

It is desired to find the general constants A_0, B_0, C_0, D_0, of the circuit as a whole that will express E_s and I_s directly in terms of E_r and I_r.

The equations of the three sections of the circuit are:—

$$E_1 = A_1E_r + B_1I_r; \quad I_1 = C_1E_r + D_1I_r \quad . \quad (3)\ (4)$$
$$E_2 = A_2E_1 + B_2I_1; \quad I_2 = C_2E_1 + D_2I_1 \quad . \quad (5)\ (6)$$
$$E_s = A_3E_2 + B_3I_2; \quad I_s = C_3E_2 + D_3I_2 \quad . \quad (7)\ (8)$$

Substituting the values of E_1 and I_1 as defined by Equations (3) and (4) in Equations (5) and (6) we have :—

$$E_2 = A_2(A_1E_r + B_1I_r) + B_2(C_1E_r + D_1I_r)$$
$$I_2 = C_2(A_1E_r + B_1I_r) + D_2(C_1E_r + D_1I_r)$$

Whence, simplifying, we have :—

$$E_2 = (A_2A_1 + B_2C_1)E_r + (A_2B_1 + B_2D_1)I_r$$
$$I_2 = (A_1C_2 + D_2C_1)E_r + (B_1C_2 + D_2D_1)I_r$$

These two equations define the general constants of two circuits in series thus :—

$$A_0 = A_1A_2 + B_2C_1$$
$$B_0 = A_2B_1 + B_2D_1$$
$$C_0 = A_1C_2 + C_1D_2$$
$$D_0 = B_1C_2 + D_1D_2$$

It should be noted here that in a symmetrical circuit (e.g. a uniform transmission line alone, or with similar transformers at either end) A is numerically equal to D, and the flow of power will produce exactly similar effects regardless of which is the sending and which the receiving end. In an unsymmetrical circuit, however, A is not numerically equal to D (e.g. a transmission line with transformers at one end only) and the direction of flow of power will influence the result.

The general constants for three circuits in series may be found similarly to the above and are :—

$$\begin{aligned}
A_0 &= A_3(A_1A_2 + B_2C_1) + B_3(A_1C_2 + C_1D_2)\\
B_0 &= A_3(A_2B_1 + B_2D_1) + B_3(B_1C_2 + D_1D_2)\\
C_0 &= C_3(A_1A_2 + B_2C_1) + D_3(A_1C_2 + C_1D_2)\\
D_0 &= C_3(A_2B_1 + B_2D_1) + D_3(B_1C_2 + D_1D_2)
\end{aligned}$$

As may be expected, if the two end portions of the circuit are similar (e.g. the transformers at either end of a uniform transmission line), i.e. if $A_1 = A_3$; $B_1 = B_3$, etc., D_0 becomes equal to A_0.

For circuits in parallel the general constants are derived as follows, where the voltages, currents and constants are as shown in Fig. 2.

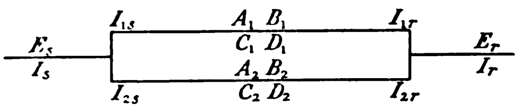


FIG. 2.

The voltage equations of the two parallel circuits are :—

$$E_s = A_1E_r + B_1I_{1r}, \quad \therefore B_2E_s = B_2A_1E_r + B_2B_1I_{1r} \quad (9)$$

$$E_s = A_2E_r + B_2I_{2r}, \quad \therefore B_1E_s = B_1A_2E_r + B_1B_2I_{2r} \quad (10)$$

Adding

$$(B_1 + B_2)E_s = (B_2A_1 + B_1A_2)E_r + B_1B_2(I_{1r} + I_{2r})$$

But

$$I_{1r} + I_{2r} = I_r, \quad \therefore E_s = \frac{A_1B_2 + A_2B_1}{B_1 + B_2}E_r + \frac{B_1B_2}{B_1 + B_2}I_r \quad . \quad (11)$$

From Equations (9) and (11) we have

$$E_s = A_1E_r + B_1I_{1r} = \frac{A_1B_2 + A_2B_1}{B_1 + B_2}E_r + \frac{B_1B_2}{B_1 + B_2}I_r$$

Whence $$I_{1r} = \frac{A_2 - A_1}{B_1 + B_2}E_r + \frac{B_2}{B_1 + B_2}I_r \quad . \quad . \quad (12)$$

Similarly $$I_{2r} = \frac{A_1 - A_2}{B_1 + B_2}E_r + \frac{B_1}{B_1 + B_2}I_r \quad . \quad . \quad (13)$$

Substituting these values in the two current equations we have :—

$$\begin{aligned}
I_{1s} &= C_1E_r + D_1I_{1r}\\
&= C_1E_r + D_1\left(\frac{A_2 - A_1}{B_1 + B_2}E_r + \frac{B_2}{B_1 + B_2}I_r\right) \quad . \quad (14)\\
I_{2s} &= C_2E_r + D_2I_{2r}\\
&= C_2E_r + D_2\left(\frac{A_1 - A_2}{B_1 + B_2}E_r + \frac{B_1}{B_1 + B_2}I_r\right) \quad . \quad (15)
\end{aligned}$$

Adding (14) and (15) we get

$$(I_{1s} + I_{2s}) = I_s = E_r\left\{C_1 + C_2 - \frac{(A_1 - A_2)(D_1 - D_2)}{B_1 + B_2}\right\} + \frac{D_1B_2 + D_2B_1}{B_1 + B_2}I_r \quad . \quad (16)$$

Equations (11) and (16) define the general constants, thus :—

$$\begin{aligned}
A_0 &= (A_1B_2 + A_2B_1)/(B_1 + B_2)\\
B_0 &= (B_1B_2)/(B_1 + B_2)\\
C_0 &= C_1 + C_2 - (A_1 - A_2)\,(D_1 - D_2)/(B_1 + B_2)\\
D_0 &= (D_1B_2 + D_2B_1)/(B_1 + B_2)
\end{aligned}$$

In practice it will be found that the third term in the expression for C_0 can generally be neglected altogether, as it is so small. It will again be noticed that for a symmetrical circuit $A_0 = D_0$.

For two identical circuits the above simplify to :—

$$\begin{aligned}
A_0 &= A_1 = A_2.\\
B_0 &= \tfrac{1}{2}B_1 = \tfrac{1}{2}B_2.\\
C_0 &= 2C_1 = 2C_2.\\
D_0 &= D_1 = D_2.
\end{aligned}$$

The general circuit constants for three circuits in parallel may be found similarly to the above and are :—

$$A_0 = \frac{A_1B_2B_3 + A_2B_3B_1 + A_3B_1B_2}{B_1B_2 + B_2B_3 + B_3B_1}$$

$$B_0 = \frac{B_1 + B_2 + B_3}{B_1B_2 + B_2B_3 + B_3B_1}$$

$$C_0 = C_1 + C_2 + C_3 - \frac{B_2(D_3 - D_1)(A_3 - A_1) + B_3(D_1 - D_2)(A_1 - A_2) + B_1(D_2 - D_3)(A_2 - A_3)}{B_1B_2 + B_2B_3 + B_3B_1}$$

$$D_0 = \frac{D_1B_2B_3 + D_2B_3B_1 + D_3B_1B_2}{B_1B_2 + B_2B_3 + B_3B_1}$$

For three identical circuits the above simplify to

$$\begin{aligned}
A_0 &= A_1 = A_2 = A_3.\\
B_0 &= \tfrac{1}{3}B_1 = \tfrac{1}{3}B_2 = \tfrac{1}{3}B_3.\\
C_0 &= 3C_1 = 3C_2 = 3C_3.\\
D_0 &= D_1 = D_2 = D_3.
\end{aligned}$$

The currents in the individual branches of the circuit may be found from Equations (12) and (13) for two circuits in parallel, and for three circuits in parallel are :—

$$I_{1r} = \frac{B_2(A_3 - A_1) + B_3(A_2 - A_1)}{B_1B_2 + B_2B_3 + B_3B_1}E_r + \frac{B_2B_3}{B_1B_2 + B_2B_3 + B_3B_1}I_r$$

$$I_{2r} = \frac{B_3(A_1 - A_2) + B_1(A_3 - A_2)}{B_1B_2 + B_2B_3 + B_3B_1}E_r + \frac{B_3B_1}{B_1B_2 + B_2B_3 + B_3B_1}I_r$$

$$I_{3r} = \frac{B_1(A_2 - A_3) + B_2(A_1 - A_3)}{B_1B_2 + B_2B_3 + B_3B_1}E_r + \frac{B_1B_2}{B_1B_2 + B_2B_3 + B_3B_1}I_r$$

The constants A, B, C, D have now to be determined for the various types of circuits that are involved in the study of transmission lines.

Transmission-Line Constants.

For the transmission line proper the following data should first be determined (for formulæ see Appendix 1):

R = resistance of one conductor in ohms per mile.
X = reactance of one conductor in ohms per mile.
G = conductance to neutral of one conductor in mhos per mile.
B = capacity susceptance to neutral of one conductor in mhos per mile.

These are the four fundamental physical constants of the line from which the general constants may be calculated as follows:—

Let $Z = R + jX$ = series impedance in ohms per mile;
and $Y = G + jB$ = shunt admittance in mhos per mile.

From here on, all the functions are expressed as complex quantities and with Z and Y expressed in the $r\underline{/\theta}$ notation the next step is to calculate the

Attenuation factor $lm = l\sqrt{(YZ)}$, and the
Surge impedance $n = \sqrt{(Z/Y)}$,

where l is the length of the line in miles.

The general constants can now be defined thus:—

$$A = \cosh lm;$$
$$B = n \sinh lm;$$
$$C = (1/n) \sinh lm;$$
$$D = A.$$

The method of calculating $\cosh lm$ and $\sinh lm$ is as follows:—

Express lm in the form $a + jb$, whence

$$\sinh (a + jb) = \sinh a \,.\, \cos b + j \cosh a \,.\, \sin b$$
$$\cosh (a + jb) = \cosh a \,.\, \cos b + j \sinh a \,.\, \sin b$$

The numerical values of these functions are best calculated by taking values of log sinh, log cosh, log sin, and log cos from tables such as the tables of hyperbolic and circular functions published by the Smithsonian Institute. It should be remembered that a and b are in radians. Tabulated values of $\cosh lm$ and $\sinh lm$ will be found in a paper entitled "The Electrical Properties of Three-Phase Transmission Lines," by E. Parry.*

For many purposes values from these tables will be close enough for the problem in hand, but even if special values are to be calculated the tables will be a valuable check on the accuracy of the work and prevent a gross error from being passed over.

Transformer Constants.

The following data should be known:—

Full-load copper loss per phase in watts.
Reactance or impedance in volts.
Iron loss per phase in watts.
Magnetizing current in amperes.

* *New Zealand Journal of Science*, 1919, vol. 2, p. 127.

These should be in terms of the line to neutral (star) voltage in three-phase systems, and all values are to be calculated as equivalent values at the high-tension star voltage.

Full load should be taken as one-third the capacity of a three-phase transformer or of a three-phase bank. Let I be the full-load current in amperes; then

$$R = \frac{\text{copper-loss watts}}{I^2} = \text{equivalent series resistance in ohms.}$$

$$X = \frac{\text{Reactance volts}}{I} = \text{equivalent series reactance in ohms.}$$
$$= \sqrt{\left[\left(\frac{\text{Impedance volts}}{I}\right)^2 - R^2\right]}$$

$$G = \frac{\text{Iron-loss watts}}{E^2} = \text{equivalent shunt conductance in mhos.}$$

$$B = \sqrt{\left[\left(\frac{\text{Magnetizing amps}}{E}\right)^2 - G^2\right]}$$
$$= \text{equivalent shunt susceptance in mhos.}$$

These four constants are exactly similar in effect to those of the transmission line, with the exception that B is in this case an inductive susceptance and is given a negative sign, thus

$$Z = R + jX = \text{series impedance in ohms,}$$
$$Y = G - jB = \text{shunt admittance in mhos.}$$

The change in the sign of B will be easily understood, as in the case of the transmission line it determines the leading charging current whilst in the case of the transformer it determines the lagging exciting current. Consider now the transformer replaced by an equivalent circuit with a series impedance Z and a shunt admittance Y as shown in Fig. 3. The admittance Y is shown

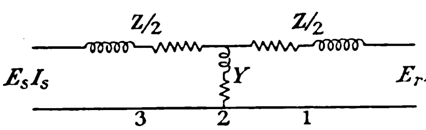


Fig. 3.

connected in the middle of the series impedance, giving a circuit practically exactly equivalent to the actual transformer.

Now the general constants of a series impedance and a shunt admittance are:—

	Series impedance	Shunt admittance
A =	1	1
B =	Z	0
C =	0	Y
D =	1	1

so that the transformer may be considered to be three circuits in series, with the following constants:—

$$A_1 = 1; \quad A_2 = 1; \quad A_3 = 1;$$
$$B_1 = \tfrac{1}{2}Z; \quad B_2 = 0; \quad B_3 = \tfrac{1}{2}Z;$$
$$C_1 = 0; \quad C_2 = Y; \quad C_3 = 0;$$
$$D_1 = 1; \quad D_2 = 1; \quad D_3 = 1.$$

We have, therefore, by substitution in the formulæ for three circuits in series, the general constants for a transformer as follows :—

$$
\begin{aligned}
A_0 &= 1 + \tfrac{1}{2}YZ \\
B_0 &= Z(1 + \tfrac{1}{4}YZ) \\
C_0 &= Y \\
D_0 &= 1 + \tfrac{1}{2}YZ
\end{aligned}
$$

We have now shown how the separate constants for sections of a system may be calculated and combined into one set of general constants. Once these general constants have been determined, the sending voltage and current can be calculated immediately from the known values of the receiving voltage and current.

It is generally convenient to adopt the receiving current vector as the vector of reference. Thus, in treating a three-phase 110 000-volt load of 12 000 kVA at 0·8 power factor, 4 000 kVA is taken as the load per phase and expressed as

$$
\begin{aligned}
I_r &= 62{\cdot}96 \text{ amperes} \\
E_r &= 63\,500\underline{/36^\circ\ 52'} = 50\,800 + j38\,100 \text{ volts.}
\end{aligned}
$$

Transformer Ratio.

It will be noted that so far no mention has been made of the transformer ratio, the problem being treated as if the transformer had approximately a 1 : 1 ratio at no load.

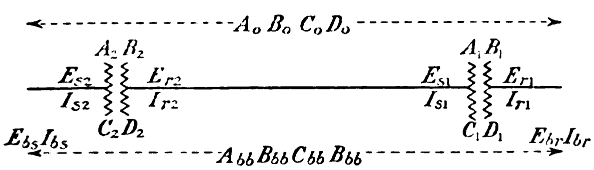


FIG. 4.

For problems dealing only with percentage variation in voltage this will generally be sufficient, but when the definite corresponding values of both sending and receiving voltages are required the actual transformer ratio must be known and taken into account.

How to take into account the ratio will best be illustrated by an example taken from the Mangahao-Wellington transmission lines. Assuming a transmission system as shown in Fig. 4 having as receiving transformers three single-phase 4 000-kVA transformers with constants A_1, B_1, C_1, D_1, and specified to have a ratio of 63 500/6 350 volts at full load, 0·8 power factor, find by trial the values of E_{r1} and I_{r1} that at 0·8 power factor will satisfy the specified conditions, i.e. that their product shall equal 4 000 kVA and that $E_{s1} = A_1E_{r1} + BI_{r1} = 63\,500$ volts. This condition is found to be satisfied by the values

$$
\begin{aligned}
E_{r1} &= 59\,250\underline{/36^\circ\ 52'} = 47\,400 + j\,35\,550 \text{ volts.} \\
I_{r1} &= 67{\cdot}515 \text{ amperes.}
\end{aligned}
$$

If now the symbol E_{r1} is retained to mean the equivalent receiving voltage in terms of the high-tension voltage as used in the formula, and E_{br} the actual low-tension busbar voltage, we have $E_{r1} = 59\,250$ and $E_{s1} = 63\,500$, from which, according to the specification, $E_{br} = 6\,350$.

Therefore $$E_{r1} = E_{br}\frac{59\,250}{6\,350}$$

Similarly if the sending transformers are of 4 000 kVA, single-phase, with constants A_2, B_2, C_2, D_2, and specified to have a ratio of 6 350/63 500 volts at no load, take $E_{r2} = 63\,500$ volts; $I_{r2} = 0$ amperes; $E_{s2} = A_2E_{r2} + B_2I_{r2} = 63\,543{\cdot}6 + j3{\cdot}6 = 63\,544$ volts. As before, letting E_{s2} be the equivalent sending voltage in terms of the high-tension voltage as found from the formula, and E_{bs} the actual busbar voltage, we have $E_{s2} = 63\,544$ and $E_{r2} = 63\,500$ from which, according to the specification, $E_{bs} = 6\,350$.

Therefore $$E_{s2} = E_{bs}\frac{63\,544}{6\,350}$$

It follows that the receiving and sending currents should also be modified in the inverse ratio, so that the equivalent $E_{r1}I_{r1}$ at the receiving end, and $E_{s2}I_{s2}$ at the sending end, shall represent the true power $E_{br}I_{br}$ and $E_{bs}I_{bs}$ respectively.

The following relations will therefore hold :—

$$
\begin{aligned}
I_{r1} &= I_{br}\frac{6\,350}{59\,250} \\
I_{s2} &= I_{bs}\frac{6\,350}{63\,544}
\end{aligned}
$$

If desired, the four values of E_{r1}, E_{s2}, I_{r1} and I_{s2}, in terms of E_{br}, E_{bs}, I_{br} and I_{bs}, may be substituted in the fundamental equations and new constants calculated that will give busbar to busbar voltages directly. The equations would then become :—

$$
\begin{aligned}
E_{bs}\frac{63\,544}{6\,350} &= A_0\frac{59\,250}{6\,350}E_{br} + B_0\frac{6\,350}{59\,250}I_{br} \\
I_{bs}\frac{6\,350}{63\,544} &= C_0\frac{59\,250}{6\,350}E_{br} + D_0\frac{6\,350}{59\,250}I_{br}
\end{aligned}
$$

If A_0, B_0, C_0 and D_0 are the combined constants of the line and transformers the busbar-to-busbar constants would therefore be :—

$$
\begin{aligned}
A_{bb} &= A_0\frac{59\,250}{6\,350} \times \frac{6\,350}{63\,544} = A_0 \times 0{\cdot}932425 \\
B_{bb} &= B_0\frac{6\,350}{59\,250} \times \frac{6\,350}{63\,544} = B_0 \times 0{\cdot}010710 \\
C_{bb} &= C_0\frac{59\,250}{6\,350} \times \frac{63\,544}{6\,350} = C_0 \times 93{\cdot}371746 \\
D_{bb} &= D_0\frac{6\,350}{59\,250} \times \frac{63\,544}{6\,350} = D_0 \times 1{\cdot}072472
\end{aligned}
$$

Transmission Lines Supplying More than One Substation.

The foregoing discussion has shown in detail the methods to be followed in handling simple transmission systems with one generating station and one substation, the equations giving the power-house busbar voltage and current in terms of the substation busbar voltage and current. It often happens, however, that

two or more substations are supplied at intervals along a transmission line, and methods for treating these cases will now be outlined.

To get one general expression for such a system that could be used in practice appears impracticable and all that will be attempted is to show how, knowing the receiving voltage at the remote end of the line and the various loads in kilovolt-amperes and their power factors, the voltage and current at any point on the system may be calculated. The no-load and load conditions will be treated separately.

Let Fig. 5 represent a transmission system with two receiving stations X and Y fed from a sending station Z, the voltages, currents and constants being as shown in the diagram.

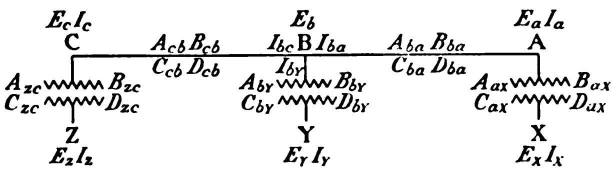


FIG. 5.

Assuming E_x, it is required to find the voltages and currents at A, B, C, Y and Z.

No-Load Conditions (I_x *and* I_y *both zero*).

The voltage and current at A are :—

$$E_a = A_{ax}E_a \quad \text{and} \quad I_a = C_{ax}E_x$$

The voltage and current at B due to the line and the transformer BAX are :—

$$E_b = A_{ba}E_a + B_{ba}I_a \quad \text{and} \quad I_b = C_{ba}E_a + D_{ba}I_a$$

The voltage at Y due to the voltage E_b at B is

$$E_b = A_{by}E_y$$

and therefore

$$E_y = E_b/A_{by} = E_b\overline{A_{by}}/A_{by}\overline{A_{by}}$$

where $\overline{A_{by}}$ is the conjugate of A_{by}.

The current at B due to the transformer BY, i.e. the exciting current at voltage E_b, is $I_{by} = C_{by}E_y$.

The total current at B is $I_{bc} = I_{ba} + I_{by}$.

The voltage and current at C are :—

$$E_c = A_{cb}E_b + B_{cb}I_{bc} \quad \text{and} \quad I_c = C_{cb}E_b + D_{cb}I_{bc}$$

The voltage and current at Z are :—

$$E_z = A_{zc}E_c + B_{zc}I_c \quad \text{and} \quad I_z = C_{zc}E_c + D_{zc}I_c$$

This step-by-step method can be extended to any number of substations. The product of the final values of voltage and current at the sending station Z will give the charging kilovolt-amperes of the system, the power factor being defined by the cosine of the angle between the voltage and current vectors.

It will be of interest to note here that if E and I are the voltage and current at any point, where $E = e_1 + je_2$ and $I = i_1 + ji_2$, then $P = e_1i_1 + e_2i_2$ and $Q = e_1i_2 - e_2i_1$, where P and Q are the energy watts and wattless volt-amperes respectively.

A rather more difficult case may arise where the line branches and supplies one or more substations on each branch. If there is only one substation on the branch line it can be dealt with by calculating the general constants of the branch line and transformers and treating it exactly as the branch BY above. If, however, the branch has more than one substation, the following method may be followed :—

Let Fig. 6 represent a transmission system branching at C and supplying two lines CDE and CBA. Assuming that E_v has been taken as the known point and E_v and I_{cd} calculated as above, it is required to find the

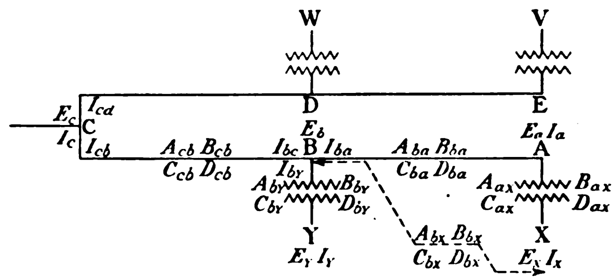


FIG. 6.

voltages and currents at A, B, Y and X as determined by the voltage E_c at C.

Calculate for the line BA and transformer AX the general constants A_{bx}, B_{bx}, etc.

The voltage and total current at B are :—

$$E_b = A_{bx}E_x = A_{by}E_y, \text{ or } E_y = A_{bx}E_x/A_{by}$$

$$I_{bc} = I_{ba} + I_{by} = C_{bx}E_x + C_{by}E_y$$
$$= C_{bx}E_x + C_{by}A_{bx}E_x/A_{by}$$

The voltage and current at C are :—

$$E_c = A_{cb}E_b + B_{cb}I_{bc}$$
$$= A_{cb}A_{bx}E_x + B_{cb}(C_{bx} + C_{by}A_{bx}/A_{by})E_x \quad . \quad (17)$$

$$I_{cb} = C_{cb}E_b + D_{cb}I_{bc}$$
$$= C_{cb}A_{bx}E_x + D_{cb}(C_{bx} + C_{by}A_{bx}/A_{by})E_x \quad . \quad (18)$$

From (17)

$$E_c = (A_{cb}A_{bx} + B_{cb}C_{bx} + B_{cb}C_{by}A_{bx}/A_{by})E_x$$

$$\therefore E_x = \frac{E_c}{A_{cb}A_{bx} + B_{cb}C_{bx} + B_{cb}C_{by}A_{bx}/A_{by}}$$

I_{cb} may be calculated step by step from E_x, or by substituting in Equation (18). The calculations may now be continued from the values E_c and I_c back to the sending station, exactly as previously described.

The above indicates the method for deriving a general equation for no-load conditions. The equations would obviously become very complicated for many substations and the step-by-step method will probably be found to be more useful in practice.

Load conditions.

Referring to Fig. 5, E_x and I_x will be known, from which may be calculated the voltage and current at A, viz.

$$E_a = A_{ax}E_x + B_{ax}I_x; \quad I_a = C_{ax}E_x + D_{ax}I_x$$

and the voltage and current at B, viz.

$$E_b = A_{ba}E_a + B_{ba}I_a; \quad I_b = C_{ba}E_a + D_{ba}I_a$$

A difficulty now arises in finding the current I_{by} at B at the voltage E_b already determined, when only the kilovolt-amperes and power factor of the load at Y are known. A complete solution is not practicable but as the exact value of the kVA is generally not known it will probably be quite near enough to estimate the low-tension voltage E_y (which can generally be done within 1 per cent) and calculate the corresponding value of the low-tension current I_y for the required kVA.

To give a clear understanding of the problem the known and unknown quantities are enumerated below and their relation is shown in the vector diagram (Fig. 7), which is not to scale. Capital subscripts in the following denote scalar values.

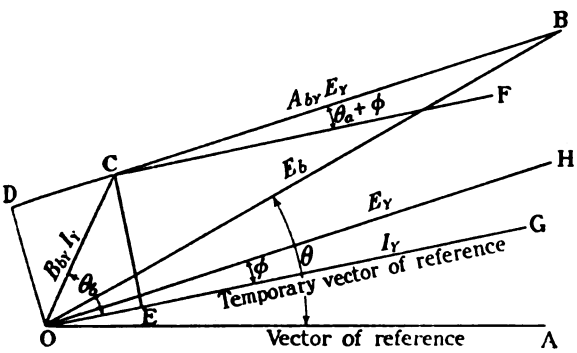


FIG. 7.

The equation to be satisfied is:—

$$E_b = A_{by}E_y + B_{by}I_y$$

where the three vectors are represented in the diagram by OB = CB + OC respectively.

Known quantities:—

E_b expressed as $E_B\angle\theta$.

I_y, numerical value only used as temporary reference vector.

A_{by} and B_{by} expressed as $A_{BY}\angle\theta_a$ and $B_{BY}\angle\theta_b$.

ϕ the phase angle of E_Y with respect to I_Y, i.e. arc cos (power factor).

Unknown quantities:—

E_Y and phase angle $\angle HOA$.

$\angle GOA$ phase angle of I_Y.

Taking OG as the temporary vector of reference, let CF be drawn parallel to OG, OD perpendicular to BC, and CE perpendicular to OG. Then:—

$$OC = B_{BY}I_Y \quad \text{and} \quad \angle COG = \theta_b$$

$$CB = A_{BY}E_Y \quad \text{and} \quad \angle BCF = \theta_a + \phi$$

Now

$$\angle DCO + \angle OCE + \angle BCF = 90^\circ = \angle COE + \angle OCE$$

$$\therefore \angle DCO = \angle COE - \angle BCF$$

$$= \theta_b - \theta_a - \phi$$

Again $\qquad DO = CO \sin \angle DCO$

Therefore

$$\sin \angle DBO = \frac{CO \sin \angle DCO}{OB} = \frac{B_{BY}I_Y \sin \angle \theta_b - \theta_a - \phi}{E_B} \quad . \quad (19)$$

$$BC = DB - DC = OB \cos \angle DBO - CO \cos \angle DCO$$

i.e. $A_{BY}E_Y = E_B \cos \angle DBO - B_{BY}I_Y \cos \angle \theta_b - \theta_a - \phi$

$$E_Y = \frac{E_B \cos \angle DBO}{A_{BY}} - \frac{B_{BY}I_Y}{A_{BY}} \cos \angle \theta_b - \theta_a - \phi \quad . \quad (20)$$

where $\angle DBO$ is defined by Equation (19).

Now $\quad \angle BOG = \angle BCF + \angle CBO = \theta_a + \phi + \angle DBO$

Therefore $\quad \angle GOA = \theta - \theta_a - \phi - \angle DOB$

We can now write:—

Phase angle of $BC = \theta - \angle DBO$

Phase angle of $E_Y = \theta - \angle DBO - \theta_a$ . . (21)

Phase angle of $I_A = \theta - \angle DBO - \theta_a - \phi$. (22)

E_y and I_y are therefore completely determined with reference to the assumed datum I_x.

The voltage and current at B can now be calculated:—

$$E_b = A_{by}E_y + B_{by}I_y \quad \text{and} \quad I_{by} = C_{by}E_y + D_{by}I_y$$

I_{by} is required for finding I_{bc} and continuing the calculation to point C (Fig. 5), and E_b should check with the value first determined, thus proving that the method gives an exact solution for the values E_y and I_y, the only approximation being that of the product E_YI_Y to the assumed value of kVA at Y.

A simpler method of treating a branch circuit with load is to assume the load at the high-tension side of the transformer and to use the inverse forms of the general equations [1 (*a*) and 2 (*a*)] to calculate the low-tension values. The actual low-tension load and power factor can only be approximated to by trial and error, for both will, in general, be different from the high-tension values assumed.

A branch line with only one substation can be treated exactly as above by using general constants for the branch line and its transformers.

The case of a branch line with more than one substation, however, presents considerable difficulty and can only be solved practically by trial and error, beginning with assumed values of E and I at the end of the branch and calculating the equivalent sending voltage at the junction. When the scalar value of this voltage has been determined sufficiently close to the actual value, the phase angles of all the quantities assumed and calculated for the branch circuit will have to be rotated by the amount of the difference between the actual and assumed values of the voltage phase angles at the junction point.

Parallel lines and banks of transformers can be treated by means of the general formulæ as developed in the previous discussion.

In conclusion, I have to acknowledge the assistance rendered by Dr. E. Marsden and the late Mr. L. Birks in reviewing and criticizing these notes.

APPENDIX 1.

Formulæ.

Resistance R = ohms per mile (see tables, e.g. *New Zealand Journal of Science*, 1921, vol. 4, p. 259).

Inductance $L = 741\cdot13 \log_{10}(ks/d)10^{-6}$ henrys per mile,

where s = symmetrical spacing, centre to centre, of conductors;
$= \sqrt[3]{(abc)}$ for unsymmetrical spacings, a, b, c;
d = diameter of conductor in the same units as s;
$k = 2\cdot568$ for single-strand conductor;
$= 2\cdot951$ for 3-strand conductor;
$= 2\cdot756$ for 7-strand conductor;
$= 2\cdot640$ for 19-strand conductor;
$= 2\cdot605$ for 37-strand conductor;
$= 2\cdot590$ for 61-strand conductor.

Reactance $X = 2\pi fL$ ohms per mile,

where f = frequency (see tables as for Resistance above).

Capacity $C = \dfrac{38\cdot83 \times 10^{-9}}{\log_{10}(s/r)}$ farads per mile (phase to neutral),

where r = radius of conductor in the same units as s.

Capacity susceptance $B = 2\pi fC$ mhos per mile.

Leakage conductance G may be taken as

$0\cdot005 \times 10^{-6}$ mhos per mile for suspension insulators.
$0\cdot008 \times 10^{-6}$ mhos per mile for pin insulators.

APPENDIX 2.

Worked Example: Mangahao–Wellington Transmission.

Transmission line, three-phase, 50-cycle, 110 000-volt conductors of 19/13 S.W.G. copper, diameter 0·460 inch, spacing right-triangle 11 ft. 6 in. horizontal, 9 ft. vertical, length 61·5 miles.

Equivalent spacing $s = \sqrt[3]{(108 \times 138 \times 175\cdot2)} = 137\cdot7$ in.

Resistance $R = 0\cdot348$ ohm per mile.

Reactance $X = 2\pi \times 50 \times 741\cdot13 \log_{10} 2\cdot64 \times 137\cdot7/0\cdot46.$
$= 0\cdot6723$ ohm per mile.

Susceptance $B = 2\pi \times 50 \times \dfrac{38\cdot83}{\log_{10} 137\cdot7/0\cdot23} \times 10^{-9}$
$= 4\cdot39196 \times 10^{-6}$ mhos.

Conductance $G = 0\cdot005 \times 10^{-6}$ mhos.

Impedance $Z = R + jX = 0\cdot348 + j0\cdot6723$
$= 0\cdot757\,\angle 62^\circ\,38'$ ohms.

Admittance $Y = G + jB = (0\cdot005 + j4\cdot392)10^{-6}$
$= 4\cdot392 \times 10^{-6}\,\angle 89^\circ\,56'$ mhos.

Attenuation factor m

$$= \sqrt{(YZ)} = \sqrt{(0\cdot757 \times 4\cdot392 \times 10^{-6})}\,\angle \tfrac{1}{2}(89^\circ\,56' + 62^\circ\,38')$$
$$= 0\cdot001824\,\angle 76^\circ\,17'$$

Surge impedance n

$$= \sqrt{\left(\frac{Z}{Y}\right)} = \sqrt{\left(\frac{0\cdot757}{4\cdot392 \times 10^{-6}}\right)}\,\angle \frac{62^\circ\,38' - 89^\circ\,56'}{2}$$
$$= 415\cdot18\,\overline{\backslash 13^\circ\,39'}$$

$lm = 61\cdot5 \times 0\cdot001824\,\angle 76^\circ\,17' = 0\cdot11215\,\angle 76^\circ\,17'$
$= 0\cdot02659 + j0\cdot10895$

$\sinh lm = \sinh 0\cdot02659 \cos 0\cdot10895 + j \cosh 0\cdot02659 \sin 0\cdot10895$

$\log \sinh 0\cdot02659 = \bar{2}\cdot42477$; $\log \cosh 0\cdot02659 = 0\cdot00015$
$\log \cos 0\cdot10895 = \bar{1}\cdot99741$; $\log \sin 0\cdot10895 = \bar{1}\cdot03657$
$\bar{2}\cdot42218$ $\qquad$ $\bar{1}\cdot03672$

$= 0\cdot02643 + j0\cdot10882 = 0\cdot11199\,\angle 76^\circ\,21'$

$\cosh lm = \cosh 0\cdot02659 \cos 0\cdot10895 + j \sinh 0\cdot02659 \sin 0\cdot10895$

$\log \cosh 0\cdot02659 = 0\cdot00015$; $\log \sinh 0\cdot02659 = \bar{2}\cdot42477$
$\log \cos 0\cdot10895 = \bar{1}\cdot99741$; $\log \sin 0\cdot10895 = \bar{1}\cdot03657$
$\bar{1}\cdot99756$ $\qquad$ $\bar{3}\cdot46134$

$= 0\cdot9944 + j0\cdot002893 = 0\cdot9944\,\angle 0^\circ\,10'$

$A_2 = \cosh lm = 0\cdot9944\,\angle 0^\circ\,10' = 0\cdot9944 + j0\cdot002893$
$B_2 = n \sinh lm = 46\cdot496\,\angle 62^\circ\,42' = 21\cdot326 + j41\cdot317$
$C_2 = (1/n) \sinh lm = 0\cdot0002697\,\angle 90^\circ = 0 + j0\cdot0002697$

Transformers sending.—Three single-phase 4 000-kVA 11 000/110 000 volts. Impedance volts = 6·15 per cent. Full-load copper loss = 26 829 watts per transformer. Iron loss = 17 060 watts per transformer. Magnetizing current = 1·411 amperes.

Full-load current $I = 4\,000 \times 1\,000/63\,500 = 63$ amperes.

Equivalent resistance $R = 26\,829/(63)^2 = 6\cdot76$ ohms.

Equivalent reactance $X = \sqrt{\left[\left(\dfrac{3\,905\cdot3}{63}\right)^2 - (6\cdot76)^2\right]}$
$= 61\cdot62$ ohms.

Conductance $G = \dfrac{17\,060}{(63\,500)^2} = 0\cdot00000423$ mhos.

Susceptance $B = \sqrt{\left[\left(\dfrac{1\cdot411}{63\,500}\right)^2 - (0\cdot00000423)^2\right]}$
$= 0\cdot0000218$ mhos.

Impedance $Z = R + jX = 6\cdot76 + j61\cdot62$ ohms.

Admittance $Y = G - jB = 0\cdot00000423 - j0\cdot0000218$ mhos.

$A_3 = 1 + \frac{1}{2}YZ = 1\cdot000686 + j0\cdot000057$
$B_3 = Z(1 + \frac{1}{4}YZ) = 6\cdot76057 + j61\cdot64132$
$C_3 = Y = 0\cdot00000423 - j0\cdot0000218$

Transformers receiving.—Three single-phase 4 000-kVA 110 000/11 000 volts.

Reactance voltage = 8·83 per cent. Full-load copper loss = 30 003 watts per transformer. Iron loss = 14 281 watts per transformer. Magnetizing current = 1·84 amperes.

As above, we have $Z = 7\cdot559 + j89\cdot02$
$Y = 0\cdot00000354 - j0\cdot0000288$

whence
$$A_1 = 1\cdot00130 + j0\cdot000049$$
$$B_1 = 7\cdot56176 + j89\cdot07786$$
$$C_1 = 0\cdot0000035 - j0\cdot000029$$

Combining the three sets of constants according to the equations

$$A_0 = 0\cdot98281 + j0\cdot00441$$
$$B_0 = 34\cdot88740 + j189\cdot99155$$
$$C_0 = 0\cdot000008 + j0\cdot00022$$
$$D_0 = 0\cdot97528 + j0\cdot00497$$

and applying to these the corrections as given under the heading "Transformer ratio" which were calculated for these transformers we have :—

$$A_{bb} = A_0 \times 0\cdot932425 = 0\cdot916393 + j0\cdot004111$$
$$B_{bb} = B_0 \times 0\cdot010710 = 0\cdot373640 + j2\cdot034785$$
$$C_{bb} = C_0 \times 93\cdot371746 = 0\cdot000747 + j0\cdot020448$$
$$D_{bb} = D_0 \times 1\cdot072472 = 1\cdot045965 + j0\cdot005327$$

These four constants when used in Equations (1) and (2) or (1a) and (2a) will give busbar voltages and currents in terms of the busbar voltages and currents at the other end of the line.

The following examples will show the method of applying these constants and the forms in which the results may be obtained. The values of load and voltage are assumed at the receiving-end low-tension busbar, and the corresponding values at the sending-end low-tension busbar are found by one application of the formulæ.

(a) *No-load conditions.*

$$E_{br} = 6\ 350\ ; \quad I_{br} = 0$$

E_{br} is taken as the vector of reference.

$$\begin{aligned} E_{bs} &= A_{bb}E_{br} + B_{bb}I_{br} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1) \\ &= (0\cdot91639 + j0\cdot00411)6\ 350 + j0 \\ &= 5\ 819\cdot1 + j26\cdot1 \\ &= 5\ 819\cdot1 \underline{/0^\circ\ 15'} \text{ volts} \end{aligned}$$

$$\begin{aligned} I_{bs} &= C_{bb}E_{br} + D_{bb}I_{br} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2) \\ &= (0\cdot000747 + j0\cdot020448)6\ 350 + j0 \\ &= 4\cdot744 + j129\cdot845 \\ &= 129\cdot931 \underline{/87^\circ\ 54'} \text{ amperes} \end{aligned}$$

$$\text{kVA} = \frac{5\ 819\cdot1 \times 129\cdot931}{1\ 000} = 756\cdot1 \text{ per phase}$$

Power factor $= \cos(87^\circ\ 54' - 0^\circ\ 15') = \cos 87^\circ\ 39'$
$= 0\cdot0410$
$= 4\cdot10$ per cent, leading

Kilowatts $= 756\cdot1 \times 0\cdot041$
$= 31$ per phase

Reactive kVA $= 756\cdot1 \times \sin 87^\circ\ 39'$
$= 756\cdot1 \times 0\cdot9915$
$= 755\cdot4$ per phase

The kilowatts and reactive kVA could have been found directly from the formulæ on page 248 thus :—

Watts $P = 5\ 819\cdot1 \times 4\cdot744 + 26\cdot1 \times 129\cdot845$
$= 27\ 607 + 3\ 388$
$= 30\ 995 = 31$ kW

Reactive volt-amperes Q
$= 5\ 819\cdot1 \times 129\ 845 - 26\cdot1 \times 4\cdot744$
$= 755\ 560 - 123$
$= 755\ 437 = 755\cdot4$ kVA

(b) *Load conditions.*—Load 4 000 kVA per phase at 0·8 power factor.

$$E_{br} = 6\ 350\underline{/36^\circ\ 52'} = 5\ 080 + j3\ 810$$
$$I_{br} = 629\cdot6 \text{ amperes}$$

I_{br} is taken as the vector of reference.

$$\begin{aligned} E_{bs} &= A_{bb}E_{br} + B_{bb}I_{br} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1) \\ &= (0\cdot91639 + j0\cdot00411)(5\ 080 + j3\ 810) \\ &\qquad + (0\cdot37364 + j2\cdot03479)629\cdot6 \\ &\quad 4\ 655\cdot28 + j\ \ 20\cdot88 \\ &\quad - 15\cdot66 + j3\ 491\cdot46 \\ &\quad \underline{235\cdot24 + j1\ 281\cdot10} \\ &= 4\ 874\cdot86 + j4\ 793\cdot44 \\ &= 6\ 836\cdot9\underline{/44^\circ\ 31'} \text{ volts} \end{aligned}$$

$$\begin{aligned} I_{bs} &= C_{bb}E_{br} + D_{bb}I_{br} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2) \\ &= (0\cdot000747 + j0\cdot020448)(5\ 080 + j3\ 810) \\ &\qquad + (1\cdot045965 + j0\cdot005327)629\cdot6 \\ &\quad 3\cdot7948 + j103\cdot8758 \\ &\quad - 77\cdot9069 + j\ \ 2\cdot8461 \\ &\quad \underline{658\cdot5394 + j\ \ 3\cdot3538} \\ &= 584\cdot4273 + j\ 110\cdot0757 \\ &= 594\cdot7036\underline{/10^\circ\ 40'} \text{ amperes} \end{aligned}$$

$$\text{kVA} = \frac{6\ 836\cdot9 \times 594\cdot7}{1\ 000} = 4\ 065\cdot9 \text{ per phase}$$

Power factor $= \cos(44^\circ\ 31' - 10^\circ\ 40') = \cos 33^\circ\ 51'$
$= 0\cdot8305$
$= 83\cdot05$ per cent, lagging.

Kilowatts $= 4\ 065\cdot9 \times 0\cdot8305$
$= 3\ 376\cdot7$ per phase.

Reactive kVA $= 4\ 065\cdot9 \times \sin 33^\circ\ 51'$
$= 4\ 065\cdot9 \times 0\cdot5570$
$= 2\ 264\cdot7$ per phase.

Summarizing, we have :—

RECEIVING END.

Assumed Values.

Volts	Amperes	Power factor	kVA	kW
6 350	—	—	0	0
6 350	629·6	80 % lag	4 000	3 200

SENDING END.

Calculated Values.

Volts	Amperes	Power factor	kVA	kW
5 819·1	129·9	4·10 % lead	756·1	31·0
6 836·9	594·7	83·05 % lag	4 065·9	3 376·7

The regulation of the line, including transformers, is thus 1 017·8 volts, or 16·0 per cent of the voltage at the receiving end.

APPENDIX 3.

USE OF CALCULATING MACHINE.

One of the commonest operations in these calculations is the evaluation of the sum of two products of complex numbers, e.g. $AE_r + BI_r$. The separate terms may be easily multiplied out on the machine, arranging the four real terms in one column and the four j terms in another, summing each column and taking particular notice of the positive and negative signs.

To obtain the scalar value from the complex form, square each number until the machine shows the sum of the squares of the two components and extract the square root as follows (these instructions are adapted for the Monroe calculating machine but will easily be followed for another make):—

Having the number to be evolved in the lower dial, clear the upper dial and keyboard, point off the number in groups of two each way from the decimal point.

Shift the carriage so that the right-hand column of the keyboard is directly beneath the position in the upper dial corresponding to the number of whole and partial groups in the lower dial.

Beginning in the keyboard column directly beneath the right-hand figure of the first or left-hand group, set up and subtract successively 1, 3, 5, 7, 9, 11, 13, etc., until no further subtractions can be made.

Increase the number on the keyboard by 1, shift the carriage one position to the left and in the keyboard column beneath the right-hand figure of the next group set up and subtract as before 1, 3, 5, etc. In setting up 11 add the left-hand digit to the figure, if any, in the preceding column.

If no subtraction can be made in any one position do not set up the 1 but, making no change, shift the carriage another position, then set up 1 and continue as before. The root appears in the upper dial; the remainder, if any, in the lower dial.

With a little practice this will be found to be a great deal faster than the use of tables of trigonometrical functions.

When trigonometrical functions are necessary it is preferable to work from tables of natural values, using the calculating machine.

THE PERFORMANCE OF AMPLIFIERS.

By H. A. Thomas, M.Sc.

[From the National Physical Laboratory; communicated by permission of the Radio Research Board.]

(*Paper first received* 15*th August, and in final form* 5*th October*, 1925; *read before the* Wireless Section, 2*nd December*, 1925.)

Summary.

The paper describes the researches which have been carried out at the National Physical Laboratory for the Radio Research Board. A standard method of testing the amplification and input impedance of an amplifier is described, and the theory of the load introduced by the amplifier as well as by reaction is shown to agree with the observed results.

Some preliminary experiments on distortion are described, output wave-forms from audio-frequency amplifiers being analysed.

Table of Contents.

Introduction.

An amplifier consists of several valves and coupling components connected in cascade, so that the total amplification effect obtained is the product of the various amplifications obtained in the individual stages. This definition excludes cases where retroaction effects from output to input via inter-electrode capacities or coupling of any type materially affect the overall amplification. In such cases the product of stage amplification is increased or decreased by such "reaction" effect. Although the ultimate output of an amplifier is in the form of power, we may regard all stages except the last as being pure potential magnifiers.

Strictly, each stage of an amplifier should perform the same function, though not of necessity in the same way. For instance, several types of coupling might be employed between two valves used for high-frequency amplification, yet if each stage is designed to amplify high-frequency E.M.F.'s, the whole series of stages would be regarded as an amplifier.

The term, unfortunately, has been extended in practice to apply to any combination of valves used for the purpose of amplifying, note-magnifying and/or rectifying, and any combination of valves fulfilling these varied functions is commercially regarded as an amplifier. For the sake of clarity such an arrangement will be termed an "amplification system," this term being more explicit than "mixed amplifier." The term "amplifier" will be applied only to a combination of components fulfilling the purpose of pure high-frequency or low-frequency amplification. Unless otherwise stated, the terms "amplifier" or "amplification system" will include all battery and output connections, i.e. it is the complete assemblage and not merely the instrument devoid of its outside circuits.

An amplification system must be of one of the following types:—

- (*a*) High-frequency stages followed by a detector.
- (*b*) A detector followed by low-frequency stages.
- (*c*) High-frequency stages, a detector, and low-frequency stages.

In the determination of the behaviour of any given amplification system, it is found expedient to split it up into its independent sections and treat each part separately. The factor of voltage amplification for both high-frequency and low-frequency sections must be obtained at the frequencies required, and the detector law connecting input voltage and rectified output must be stated. The internal behaviour cannot be analysed if an overall input-output expression only is given.

The performance of any amplifier must be expressed in terms of three distinct properties:—

1. Its voltage amplification.
2. Its effect upon the circuit to which it is connected.
3. Its distortion of wave-form.

These three properties are intimately related to each other, but the amount of experimental work carried out has been insufficient for an attempt to be made to correlate any one property with any other. Valve noises, which in a multi-stage audio-frequency amplifier usually determine the limiting number of cascade valves, are a special property of amplifiers and will not be dealt with here. Such noises are more a matter

of valve design. The three essential characteristics are therefore treated separately at present.

A method of determining the voltage amplification of high-frequency or low-frequency amplifiers is described in detail, and the effect of the amplifier on the input circuits is analysed. With reference to the distortion produced by low-frequency amplifiers, the results of some preliminary experiments are given, but more information is needed before a complete study of distortion can be attempted. This Section is therefore very fragmentary, and is given in order to demonstrate the types of distortion met with in practice and to show the magnitude of the distortion that may be anticipated in practical cases.

Section 1. The Measurement of Voltage Amplification.

(*a*) *Practical difficulties.*—At first sight it would appear a comparatively simple matter to inject known E.M.F.'s to the input terminals of the amplifier, and measure these E.M.F.'s for a constant known output, but there are many difficulties which render such an operation exceedingly difficult.

In the first place, since the voltage amplification is critically dependent upon the filament emission and the high-tension voltage, it is desirable to adjust each valve of a cascade amplifier individually to give its optimum voltage factor. In practice, several filaments are bunched together and controlled by a coarse rheostat. It is therefore usually impossible to obtain the maximum output from any given set of triodes. Every disturbance of the original circuit, such as will be produced by the insertion of measuring instruments, will modify the characteristics and, if this insertion takes place between the input and output, the disturbance so produced may be very serious. This forms one of the major difficulties of measurement. Again, actual stage amplification is not constant for all inputs but appears to increase with weak inputs.

The output has either to be determined or kept constant, and, whatever method be adopted, the output must be measured in some way.

The determination of the amplification of the system is of value only when the E.M.F.'s and currents with which it is dealing are of the same order as those encountered in practical operation on a receiving antenna. The current in the telephones for an average type of signal is only of the order of micro-amperes, and such instruments as the Duddell reflecting thermo-galvanometer and electrostatic voltmeters can only be used for loud signals, failing completely to measure the feeble outputs required. Indirect methods such as the valve or crystal rectifier and "slide back" method give rather doubtful accuracy and always introduce not only shunting loads but large earth capacities due to the batteries forming the appendages of such auxiliary measuring circuits.

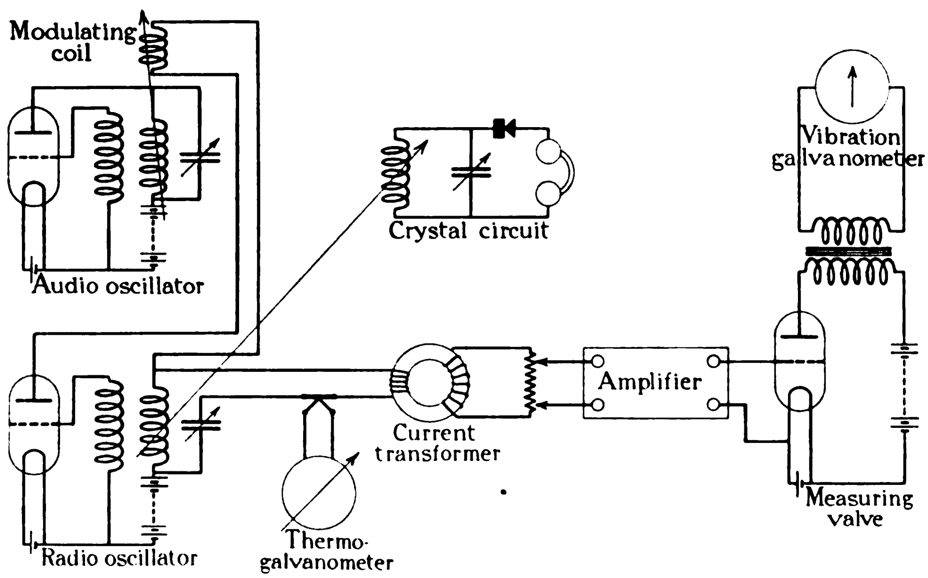


Fig. 1.

The method which has most often been adopted in this class of work consists of telephone comparisons. The difficulty of matching two sounds in intensity is well known, and limits the accuracy of such methods owing to the insensitivity of the human ear to small pressure-changes.

Again, perhaps the most serious difficulty in so matching telephone sounds lies in the fact that the pressure wave delivered to the ear is usually not sinusoidal and the type of wave given under the two balance conditions is dissimilar. It will be shown later that the output wave-forms from even the simplest type of single-stage amplifier are seriously distorted from the original sinusoidal input form, and it is quite true to state that the physiology of the human ear is so little understood that even if a balance is observed between two dissimilar waves, it is difficult to know what such a balance means.

Since such distortions of initial form take place throughout the amplifier, we are left with two methods of measurement :—

(i) The R.M.S. value of the output-current wave.
(ii) The value of the fundamental component of the complex wave.

Most measurements give (i), and it has been found only approximate to consider this value as representing the output. This determination requires also a knowledge of the wave-form to have much significance. However, if (ii) is measured, this does give the true amplification of the original wave due to the system, the harmonics produced being considered merely as the result of secondary effects which can be dealt with separately.

The methods of measuring amplification due to Jordan * and Napier-Smith † suffer by the adoption of a telephone comparison as the final limit of measurement. About 5 per cent is the limit of accuracy with a trained observer, and many observations produce nerve strain upon the operator. The latter method of determination of small mutual inductances at high audio frequencies.

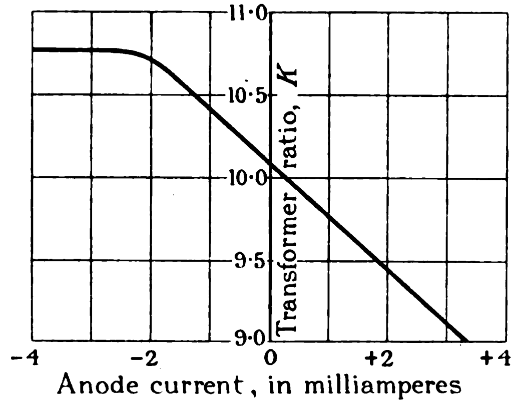


FIG. 2.

(b) *General method.*—The method adopted for measuring output employs a vibration galvanometer in con-

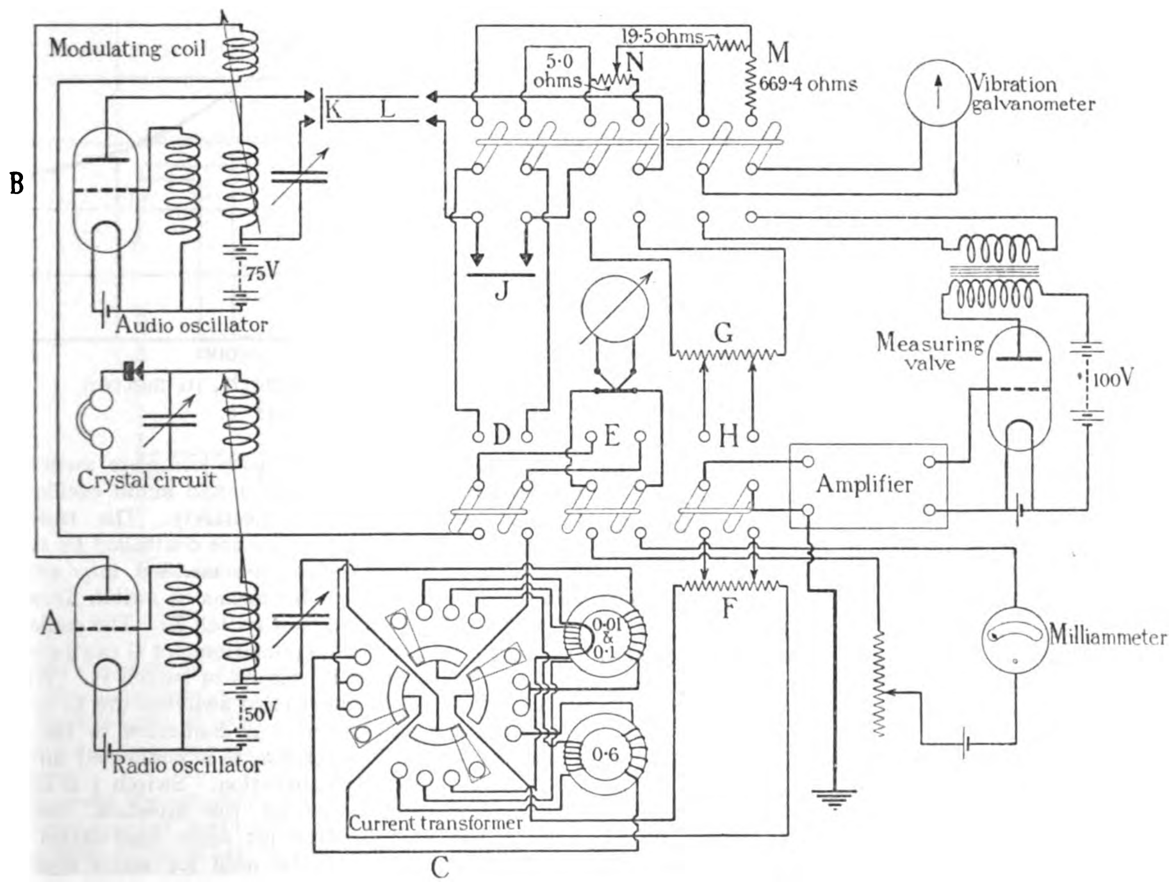


FIG. 3.

known mutuals cannot be applied to cases with very large step-up ratios, owing to the inaccuracy in the nection with a current transformer, the resistance of the secondary of the transformer, which is in series with the galvanometer, being about equal to the sum of the motional and static resistances of the galvano-

* *Proceedings of the Physical Society of London*, 1919-20, vol. 32, p. 105.
† *Ibid.*, 1919-20. vol. 32. p. 116.

meter, the former being the largest portion of the effective galvanometer resistance.

Small, known E.M.F.'s cannot easily be obtained by a series of simple potentiometers, and thus a step-down radio-frequency current transformer * was adopted in conjunction with a calibrated high-frequency resistance potentiometer across the secondary. The current in the primary is measured by means of a thermo-junction and galvanometer. A ratio of E.M.F.'s of $1/10^5$ can be obtained by this method, the accuracy of measurement falling only towards the smaller values of injected voltage.

Since for the measurement of high-frequency amplifiers the output must be of audible frequency to operate the galvanometer, the radio output is modulated by means of an aperiodic coupling coil (coupled to an audio source) in series with the anode of the oscillator valve.

The general scheme of the apparatus is shown in Fig. 1. If the rectifier characteristic is required, a definite percentage of modulation is necessary. This is

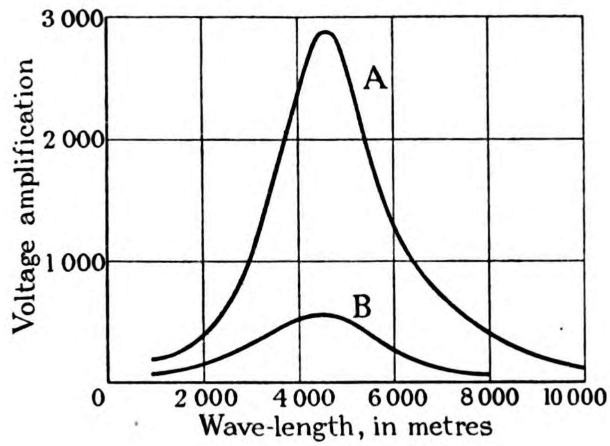


Fig. 4.

provided for by always setting the aperiodic coupling coil to give complete (or 100 per cent) modulation. The method of determining this condition is by means of a local tuned crystal receiving circuit coupled to the radio oscillator. When the source is over-modulated, a second harmonic is easily detectable in the rectified current as observed by telephones, and the point where this just vanishes gives the completely modulated condition. Tests with an electrostatic voltmeter demonstrate that this point can be determined audibly with accuracy.

The galvanometer can be calibrated directly from the audio source, and the current transformer is also calibrated for ratio, the combination forming a method of measuring the output current at the particular frequency of 1 000 which represents an average for telegraphic signals. The calibration of the transformer is dependent upon the d.c. anode current flowing through the primary, as the characteristic working point on the *B–H* curve is altered by such current. Fig. 2 gives the calibration of this transformer and shows what large changes in ratio can be expected from comparatively small polarizing anode currents.

For the determination of high-frequency voltage amplification a constant modulation is all that is required, the calibration of the galvanometer being necessary only for the absolute determination of the rectifier characteristic.

To determine the amplification factor of the audio stages, the audio source is injected directly by means of a potentiometer with a known shunt, and the output is measured as before. It was found that the current sensitivity of the vibration galvanometer varied considerably and thus a quick-switching arrangement was devised by means of which the galvanometer could be directly calibrated from the audio source in terms of a vacuo-junction deflection, which in turn could be instantly calibrated by direct current and a milliammeter. In this way, both input and output can be referred directly to a d.c. instrument, and errors due to inconstancy of calibration are eliminated.

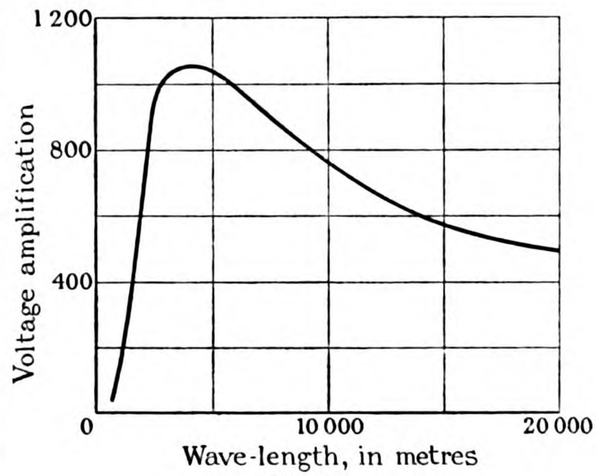


Fig. 5.

The final arrangement with complete switchgear is shown in Fig. 3. The radio and audio oscillators are shown at A and B respectively. The three high-frequency transformer ratios are controlled by switch C. The thermo-junction can be inserted into either the radio or audio source by means of switch D, and can be calibrated by means of switch E. The radio potentiometer F or the audio potentiometer G can be switched on to the amplifier by means of switch H. When the three double-pole interlocked switches are in the lower position the galvanometer is connected to the output, whereas in the top position it is connected directly to the audio source for calibration. Switch J is closed for calibration and works on the interlock. Switch K closes the audio source for radio modulation and L permits the source to be used for audio injection or galvanometer calibration. The standard shunts are shown at M, and the potentiometer N is used for calibration.

Both high-frequency and low-frequency amplifiers forming part of an amplification system can be quickly measured by this means. The only difficulty lies in the direct induction due to the source at a considerable

* D. W. Dye: "Producing Small Voltages at Radio Frequencies," *Journal I.E.E.*, 1925, vol. 63, p. 597.

distance from the amplifier under test. This difficulty was almost entirely eliminated by sheathing all the radio oscillator leads in copper tubing.

(*c*) *Discussion of results obtained.*

High-frequency amplifiers.—So far as high-frequency amplification is concerned, it seems apparent from the results obtained that the net effect of the many factors which can only be approximated in design gives very variable figures for amplification. As an example, two apparently identical 3-stage amplifiers, transformer coupled, were measured, with the results shown in Fig. 4. In curve A, the factor per stage at a wave-length of 4 700 m is considerably greater than the factor of the triode. It is apparent that, in this case, retroaction effects combine to increase the overall amplification, whereas in curve B the phasing is such as to reduce the amplification. Since such retroactive effects form an inherent property of any amplifier and are dependent upon inter-electrode capacities, stray lead capacities and leaks, it is reasonable to expect large variations between amplifiers built to similar specifications.

Fig. 5 gives the overall voltage amplification of a 6-stage resistance capacity amplifier, from which it will be noticed that below 4 000 m the shunting effect due to the self-capacity of the anode resistances seriously reduces the amplification. The more gradual fall at higher wave-lengths is attributed to the fact that the coupling condensers are not large enough at the lower frequencies.

Fig. 6 gives the amplification of a 6-valve untuned transformer-coupled amplifier with various inputs on the grid, from which it will be observed that the amplification appears to fall with increasing input.

It has been stated by several authorities that the voltage amplification falls with weak inputs, but the inputs for which this effect is claimed are of the order of a few microvolts and are smaller than any input measured here. The curve shown in Fig. 6 may therefore bend back to the origin, but no measurements have been taken to confirm this. The evidence for this effect may depend upon distortion which will seriously affect the R.M.S. value of the current and may not be a genuine reduction of amplification of the fundamental. The discrepancies arising due to a neglect of the harmonics present may be, as shown later, very serious.

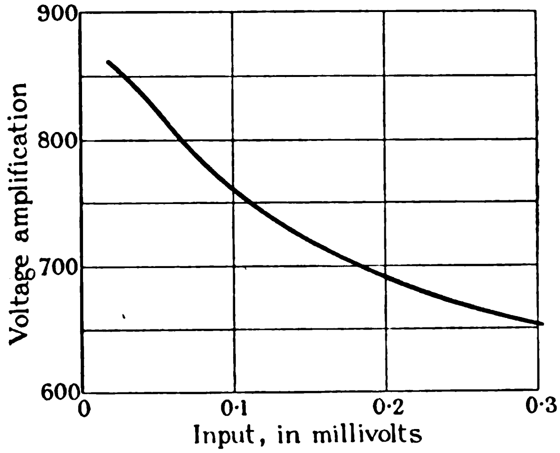


FIG. 6.

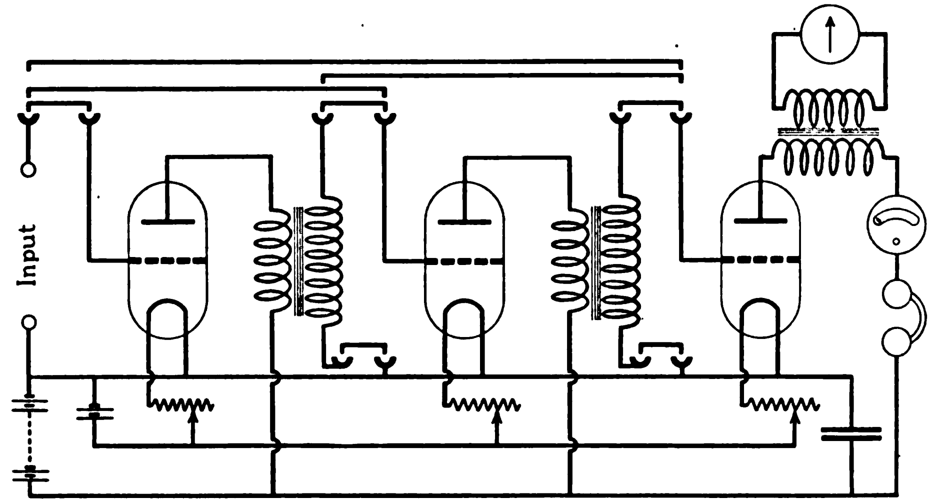


FIG. 7.

The behaviour of the detecting valve has been found in every case to depart only very slightly from the theoretical square law; in fact this law can in most instances be assumed.

Low-frequency amplifiers.—The measurement of the voltage amplification of a low-frequency amplifier presents less difficulty. The inter-electrode impedances at low frequencies are large and their shunting effects almost negligible. Induction can be entirely eliminated with care, and measurements to less than ½ of 1 per cent can be obtained.

Several standard audio amplifiers were tested at a frequency of 1 000, and it was found that the overall amplification of several cascade stages was less than the product of the individual stages. A special experimental 2-stage amplifier was built and with

this it was found that very consistent results could be obtained.

The amplifier output was measured by means of a special calibrated measuring valve as shown in Fig. 7. By means of links and mercury cups, the input could be switched on to the measuring valve, stage 1 and the measuring valve, or stage 1, stage 2 and the measuring valve. The voltage amplification of each stage was in this way compared with the overall amplification of the two stages in cascade. With definite high tension, low tension and grid bias, the amplification of stage 1 was found to be 21·9, and of stage 2, 19·65. When these two stages were coupled together, the first gave 22·2 and the second 19·2, the overall amplification thus being 426 for the two stages in cascade.

This means a gain of 1 per cent on the first stage, due to retroaction from the second and to a weaker input, and a loss of 2 per cent on the second due to the fact that the input wave-form to this valve is now no longer sinusoidal. The overall loss for the two stages is 1 per cent, the theoretical figure being 433, the product of the two initial determinations.

The Smith-Napier method of testing gave 21 for each stage and thus shows good agreement with a poorer sensitivity. The effect of the high-tension condenser of several microfarads was found to be very pronounced, the amplification falling considerably when a smaller condenser was used. This effect is probably due to the resistance of the high-tension battery.

The effect of inserting a small capacity of 100–1 000 $\mu\mu$F between the two windings of the transformer is slightly to increase the amplification, due to the increase in the electrostatic coupling between the windings. A capacity of 1 000 $\mu\mu$F increased the amplification by 5 per cent.

These tests show that it is possible to construct a 2-stage amplifier in which little loss takes place, if the components are judiciously separated. The maximum figure of 420 may be obtained, if separate high-tension batteries be used for each stage without the use of a high-tension condenser. Separate low-tension batteries produce an increase of 4 per cent in overall amplification.

SECTION 2. THE INPUT IMPEDANCE OF AN AMPLIFIER.

(*a*) *Discussion of methods of measurement.*—The effect of the amplifier upon the tuned input circuit is twofold, viz.—

(*a*) To increase or decrease its effective resistance, due to the power taken from (or delivered to) this circuit by the valve amplifier.

(*b*) To alter the tuning of the circuit due to the shunt capacity of the input circuit of the amplifier.

The amplifier may be looked upon as an impedance load across the tuned circuit. To determine this load it is necessary to find the effective change in the high-frequency resistance of the resonant circuit as well as the shift in the resonant frequency due to the amplifier.

The usual method of determining the high-frequency resistance of the tuned circuit consists of inserting a known non-inductive resistance into the circuit and determining the fall of current in that circuit, or the fall in voltage across the circuit. If the voltage across the condenser is V before insertion and V_r when a resistance R is inserted, we have

$$\frac{V}{V_r} = \frac{R_e + R}{R_e}$$

where R_e is the circuit resistance.

Very inconsistent results were obtained with this method, often of the order of 100 per cent. These errors are attributed to the fact that the mechanical shape of the tuned circuit is modified by the insertion, and the effective E.M.F. in the circuit was so varied.

It appears that with large currents and low amplification the E.M.F. can be inserted virtually at one

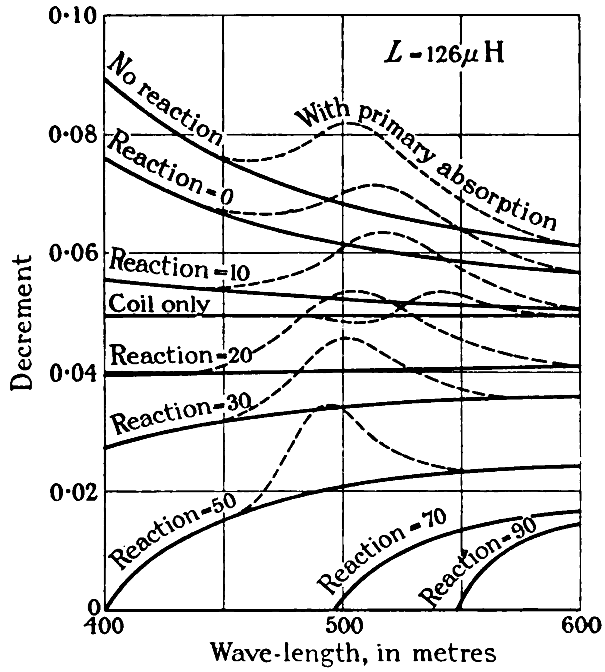


FIG. 8.—Decrement curve: stud 2.

point in the resonant circuit (as in the case of a deliberately inserted inducing coil), thus approaching the ideal theoretical conditions, but when the injected E.M.F. is very small and is picked up by a stray field in the neighbourhood of the amplifier, the injected E.M.F. will vary materially with any changes in the mechanical formation of the circuit. The "feed-back" effect due to retroaction is dependent upon the resistance of the input circuit, and any artificial change in this resistance will modify the amplifier condition.

When a 6-stage high-frequency amplifier is used, the injected E.M.F. is so small that direct pick-up induction from the oscillator is sufficient to give large outputs. In this particular case the injected E.M.F. was of the order of 1 mV to give a weak signal of about 6 μA in the output circuit, the field from a weak oscillator 15 ft. away being sufficient for this output. Such distant injection has the advantage that the tuned circuit is in no way modified by local coupled circuits.

The inserted-resistance method had therefore to be abandoned when such weak signals were being dealt with. A resonant method of determining the high-

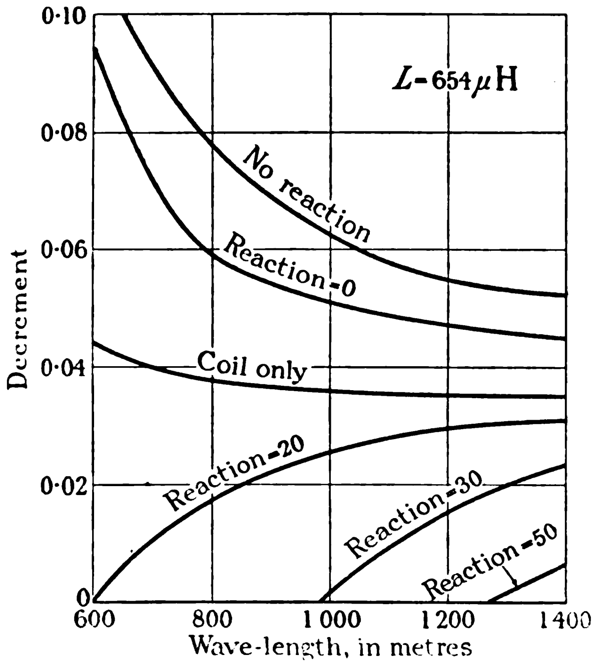


FIG. 9.—Decrement curve: stud 3.

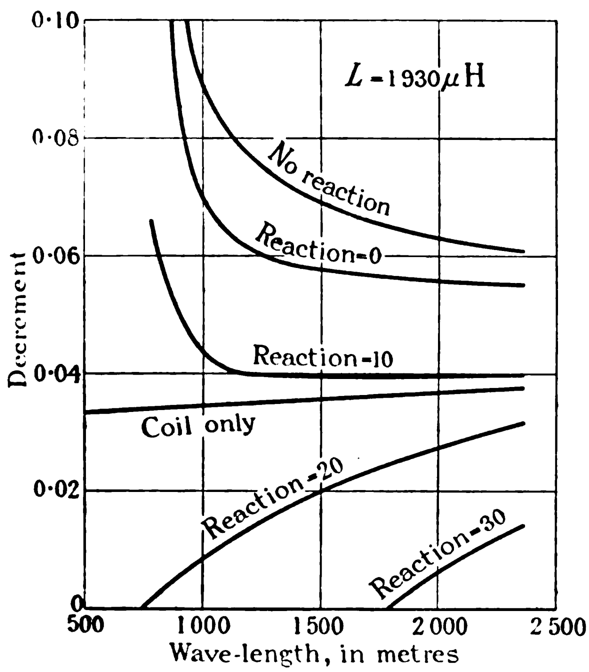


FIG. 10.—Decrement curve: stud 4.

frequency resistance had therefore to be resorted to and it was found that this method gave very excellent results.

(*b*) *The resonance method of measuring the effective resistance of an oscillatory circuit.*—If the resonance curve of a tuned circuit is obtained, the decrement of the circuit is given by either of the following formulæ :—

$$\delta = \pi \frac{C_r - C}{C} \sqrt{\frac{1}{(I_r/I)^2 - 1}} \quad . \quad . \quad . \quad (1)$$

where C_r and I_r are the values of capacity and current

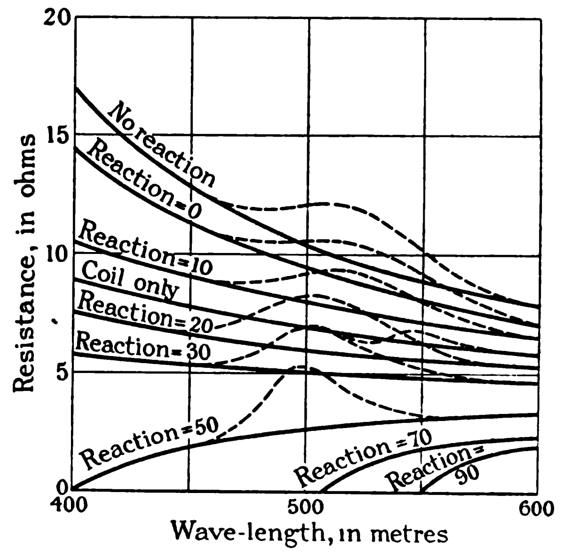


FIG. 11.—Resistance curve: stud 2.

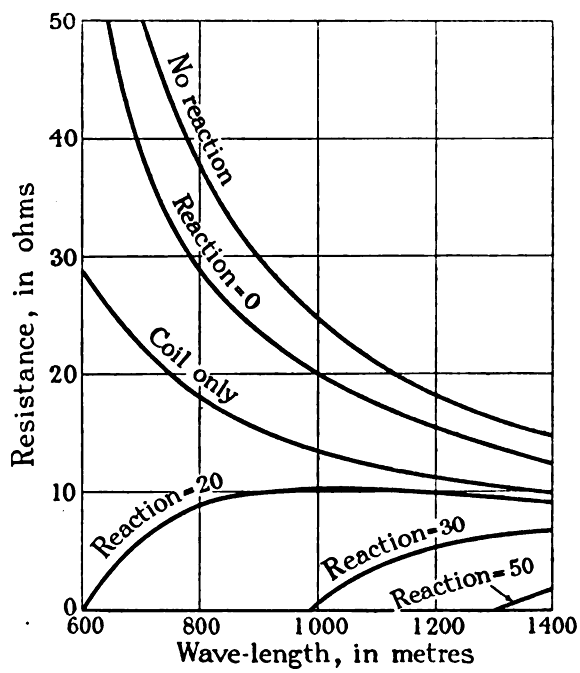


FIG. 12.—Resistance curve: stud 3.

at resonance, and C and I are values at any other point on the curve, or

$$\delta = 2\pi \frac{f - f_r}{f_r} \sqrt{\frac{1}{(I_r/I)^2 - 1}} \quad . \quad . \quad . \quad (2)$$

where f_r and f are the frequencies at resonance and any other point respectively.

If a constant-frequency source be applied to the tuned circuit, and its tuning condenser be altered, a

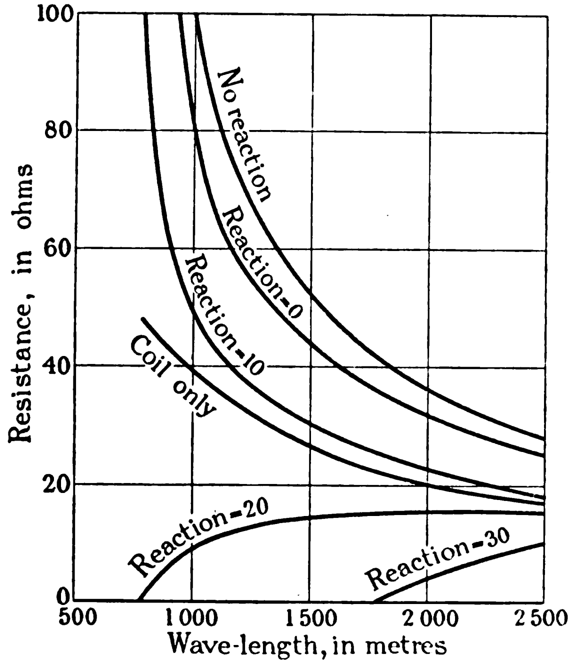


FIG. 13.—Resistance curve: stud 4.

resonance curve can be plotted. This method, however, means a calibration of the tuned circuit condenser, which forms part of the losses to be measured and also

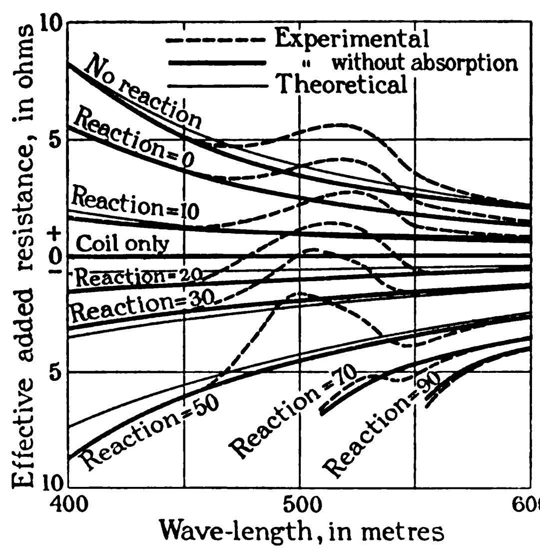


FIG. 14.—Effective added resistance due to amplifier: stud 2.

slightly disturbs the amplifier conditions. The proximity of an operator also seriously modifies the injecting field.

For these reasons, therefore, it was thought preferable to keep the test-circuit constant and to vary the input frequency. As the resonance curve is obtained with changes of less than 1 per cent in frequency, great accuracy of oscillator constancy and calibration is required.

An oscillator was therefore built with a standard condenser and a special 40 $\mu\mu$F condenser in parallel. This condenser was controlled at a distance of several feet and was calibrated to $0 \cdot 1$ $\mu\mu$F. The self-capacity of leads and coils was measured and thus the value of C_r was accurately known. The rectifier was found to follow a square-law curve to within $\frac{1}{2}$ of 1 per cent and therefore the vibration galvanometer scale was modified to a square law, thus saving much labour in calculation.

It was found possible to plot resonance curves with this apparatus quickly and with a remarkable accuracy.

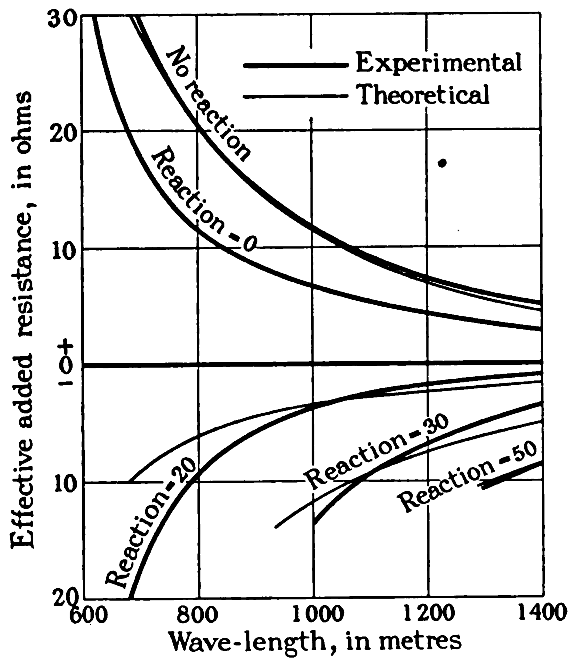


FIG. 15.—Effective added resistance due to amplifier: stud 3.

Of a total of about 300 such curves, the average error between several determinations of decrement from one curve was not greater than 1 per cent and the individual error was never greater than 5 per cent. Many interesting and important points would have been missed if a more approximate method had been adopted.

(c) *The effective load on the resonant circuit due to the amplifier.*—Decrement curves obtained for three inductance ranges are shown in Figs. 8, 9 and 10. These curves do not diverge by more than $\frac{1}{2}$ of 1 per cent from the actual points taken. In Fig. 8 a peculiar absorption is noted at a wave-length of 505 m, which occurs at all settings of reaction. This is due to the natural wave-length of a very loosely coupled aerial tuning coil which forms part of the tuning panel.

The decrement of the tuned circuit without an amplifier is also shown, this being determined by plotting resonance curves as before with a vacuo-junction in series as a recording instrument, the source being a powerful calibrated oscillator.

From these curves the resistance of the circuit was plotted, since $\delta = R/(2fL)$, where R = resistance, f = frequency, and L = inductance of tuned circuit, in henrys. These curves are shown in Figs. 11, 12 and 13. By taking the resistance of the circuit (without the amplifier) as datum and plotting the change in effective resistance with various reaction settings, the curves shown in Figs. 14, 15 and 16 are obtained. They represent the effective added positive or negative resistance produced by the amplifier for different settings of the reaction coil and at different frequencies.

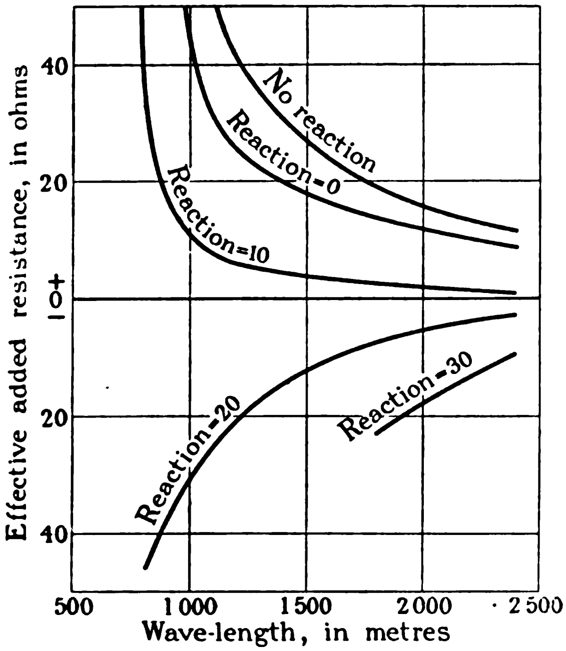


FIG. 16.—Effective added resistance due to amplifier: stud 4.

The following points are at once noticed :—

(1) The effective resistance load cannot change sign at varying frequencies.

(2) All curves appear to bear a definite mathematical relationship to each other.

(3) The departures from the mean form of the curves occurs only near to oscillation, when instability occurs.

In most of the cases given, oscillation may be obtained when the tuning condenser is very small, i.e. the curve may suddenly bend back and give a negative resistance. As this period was always unstable, it was deemed unwise to consider these conditions in the curves.

(*d*) *Theoretical treatment.*—Miller's analysis * of the effect of an amplifier on an outside circuit cannot conveniently be adapted to frequency variations. The theory has therefore been attacked from first principles, and practical expressions have been obtained for the particular cases under consideration.

The amplifier may be considered as a resistance and capacity in series acting as a load across the tuned circuit. Since the effect of this load is always positive without reaction, the resistance must also be positive. Let R_1 and C_1 be the effective resistance and capacity respectively of the amplifier input circuit. We have to find R_1 and C_1 in terms of the effective increase of resistance, ΔR, in the tuned circuit, the initial high-frequency resistance of which is R. In the vector diagram shown in Fig. 17, E_c and I_1 represent the E.M.F. and current in the branch circuit, the leading angle being ϕ_1. The main current I will equal the vectorial sum of I_1 and $I_c = E_c\omega C$. The increased E.M.F. due to the load is $I\Delta R = E_c \sin\theta$, and the resonant condition is fulfilled when $\omega LI = E_c \cos\theta$, the effect of the load thus being to alter the value of C to tune to any definite frequency.

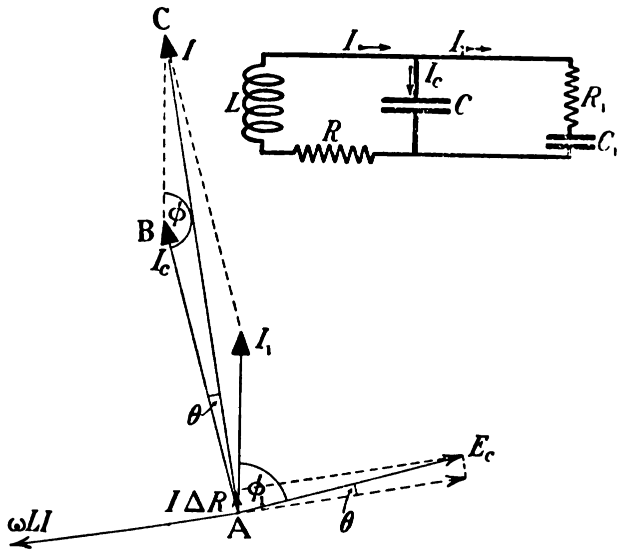


FIG. 17.

From the triangle A B C we have

$$\frac{I_1}{I} = \frac{\sin\theta}{\sin\phi} = \frac{\sin\theta}{\cos\phi_1} \text{ (since } \phi_1 = \phi - \tfrac{1}{2}\pi)$$

$$I_c = E_c\omega C = I_1 Z\omega C$$

where $Z = \sqrt{[R_1^2 + (1/\omega C_1)^2]}$ and $E_c \cos\theta = \omega LI$ at resonance,

$$E_c = \frac{\omega LI}{\cos\theta} = I_1 Z$$

$$\therefore \frac{I_1}{I} = \frac{\omega L}{Z\cos\theta} = \frac{\sin\theta}{\cos\phi_1}$$

Now $$\sin\theta = \frac{\Delta R}{\sqrt{[\Delta R^2 + (\omega L)^2]}}$$

$$\cos\theta = \frac{\omega L}{\sqrt{[\Delta R^2 + (\omega L)^2]}}$$

and $$\cos\phi_1 = \frac{R_1}{\sqrt{[R_1^2 + (1/\omega C_1)^2]}} = \frac{R_1}{Z}$$

$$\therefore \frac{\omega L}{Z} = \frac{\sin\theta\cos\theta}{\cos\phi_1} = \frac{\Delta R\omega LZ}{\{\Delta R^2 + (\omega L)^2\}R_1}$$

$$\therefore R_1\{\Delta R^2 + (\omega L)^2\} = \Delta RZ^2$$

$$\therefore \Delta R^2 R_1 - \Delta RZ^2 + R_1(\omega L)^2 = 0$$

* "Dependence of the Input Impedance of a Three-Electrode Vacuum Tube upon the Load in the Plate Circuit," *Scientific Papers of the Bureau of Standards*, No. 351.

Solving this quadratic, we get

$$\Delta R = \frac{Z^2 \pm \sqrt{[Z^4 - 4(R_1\omega L)^2]}}{2R_1}$$

$$= \frac{Z^2}{2R_1}\left[1 \pm \left\{1 - 4\left(\frac{R_1\omega L}{Z^2}\right)^2\right\}^{\frac{1}{2}}\right]$$

and, since $\left(\frac{R_1\omega L}{Z^2}\right)^2$ is small compared with unity

$$\Delta R = \frac{Z^2}{2R_1}\left[1 \pm \left\{1 - 2\left(\frac{R_1\omega L}{Z^2}\right)^2\right\}\right]$$

$$= \frac{Z^2}{2R_1} \times \frac{2(R_1\omega L)^2}{Z^4}$$

$$= \frac{R_1(\omega L)^2}{Z^2}$$

if the plus sign $\left(\text{which gives } \Delta R = \frac{Z^2}{R_1} \doteqdot 10^9\right)$ is neglected,

$$\therefore\ \Delta R = \frac{R_1(\omega L)^2}{R_1^2 + [1/(\omega C_1)]^2}$$

To find R_1 and C_1 for given values of ΔR, L and ω, we solve the two simultaneous equations given by

$$R_1^2\Delta R - R_1(\omega L)^2 + \Delta R/(\omega C_1)^2 = 0$$

In Fig. 14, taking the curve of no reaction, we find that $\Delta R = +8\cdot25$ ohms at 400 m and $+2\cdot15$ ohms at 600 m. From these values we get $R_1 = 20\ 800$ ohms, and $C_1 = 9\cdot9\ \mu\mu$F.

Substituting these values in the general expression we obtain a theoretical curve, the correlation with the experimental being within 10 per cent.

A few of the values obtained are given in Table 1.

TABLE 1.

Wave-length	ΔR (theoretical)	ΔR (experimental)
m		
400	8·25	8·25
450	5·50	5·20
500	3·90	3·50
550	2·87	2·60
600	2·15	2·15

TABLE 2.

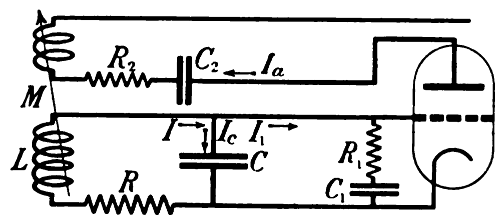
Wave-length	ΔR (theoretical)	ΔR (experimental)
m		
700	28·95	29·0
800	20·8	20·4
900	15·03	15·4
1 000	11·92	11·8
1 100	9·26	9·2
1 200	7·28	7·3
1 300	5·82	6·0
1 400	4·67	5·2

In Fig. 15 we get $R_1 = 87\ 600$ ohms and $C_1 = 9\cdot0\ \mu\mu$F. The values obtained from them and the theoretical curve are given in Table 2.

The positive load introduced by the amplifier can therefore be expressed in terms of a definite resistance and capacity, this capacity appearing to remain constant at all frequencies and values of the inductance in the resonant circuit. However, the resistance values obtained were found to differ for various values of L as follows:—

L	R_1
$\mu\mu$H	ohms
126	20 800
654	87 600
1 930	249 000

The value of R_1 increases with L and approximately follows the law $R_1 \propto L^{0\cdot8}$.



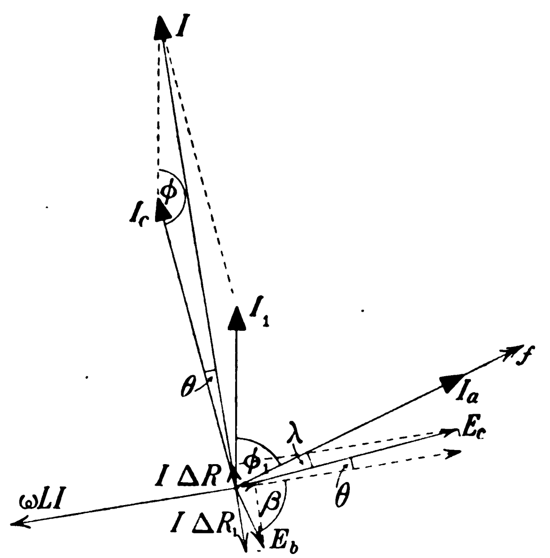


FIG. 18.

C_1 can be determined with an accuracy of about 5 per cent, but it is impossible to obtain a greater accuracy than 10 per cent for the value of R_1 with the limits of 1 per cent imposed by experimental error.

(*e*) *The theory of retroaction.*—The load imposed on the tuned circuit may be positive or negative when reaction is employed. These reaction curves possess properties similar to those of the curves of a pure load on the oscillatory system, and could be expressed in terms of a constant series capacity and resistance shunt. However, the results obtained would serve no more useful purpose than the diagrams themselves. It was thought preferable to express the reduction in the

effective load due to reaction in terms of the actual electrical constants of the anode circuit, in order to show whether the fundamental theory would explain the experimental results.

In Fig. 18 the plate-circuit impedance is represented by a capacity and resistance in series, the resistance consisting of the anode-filament resistance of the triode and the capacity (the self-capacity of the iron-cored intervalve transformer), which will probably form a lower reactance at these frequencies than the inductance.

A fourth E.M.F. vector E_b' is thus inserted into the resonant circuit which has two components, the one in phase with I producing a reduction of the effective resistance, and the other quadrature component altering the resonant conditions slightly.

The phase angle in the anode circuit is denoted by the angle λ, and the reduction of circuit resistance is given by $\Delta R_1 = (E_b/I) \sin \beta$.

The resonant condition gives from the vector diagram

$$\omega LI = \Delta RI \cot\theta + \Delta R_1 I \cot\beta$$
$$\therefore \omega L = \Delta R \cot\theta + \Delta R_1 \cot\beta$$
$$\therefore \Delta R_1 = \frac{\omega L - \Delta R \cot\theta}{\cot\beta}$$

Now $\cot\beta = \tan(\theta + \lambda)$.

Assuming $R_2 >> 1/(\omega C_2)$, and knowing from experiment that $\tan\theta \doteq \Delta R/(\omega L) << 1$, we have

$$\tan\theta = \theta \propto \Delta R/\omega = (p/\omega)\Delta R$$

and $$\tan\lambda = \lambda \propto (1/\omega) = q/\omega$$

$$\therefore \tan(\theta + \lambda) = \theta + \lambda = (p\Delta R + q)/\omega = \cot\beta$$
$$\therefore \Delta R_1 = \frac{\omega L - \Delta R\omega/(p\Delta R)}{(p\Delta R + q)/\omega}$$
$$\therefore \Delta R_1 = \frac{\omega^2[L - (1/p)]}{p\Delta R + q}$$

where p and q are constants for any given curve.

From Fig. 14 (reaction = 0) we get

$$p = 7\,930, \text{ and } q = -0{\cdot}117 \times 10^6$$

and the equation of the curve is given by

$$\Delta R_1 = \frac{0{\cdot}00607 Y^2}{0{\cdot}117 - 0{\cdot}00793\Delta R}$$

where $Y = \omega/10^6$.

This curve, when plotted against the experimental values, gives very close agreement, as shown in the figure, and demonstrates that the results can be expressed theoretically. Similarly, in Fig. 15 (reaction = 0) we get

$$p = 1\,530 \text{ and } q = -0{\cdot}1733 \times 10^6$$

and the equation of the curve is given by

$$\Delta R_1 = \frac{0{\cdot}1957 Y^2}{0{\cdot}1733 - 0{\cdot}00153}$$

where $Y = \omega/10^6$.

Since $$\tan\lambda = X_a/R_a = q/\omega$$

X_a is small compared with R_a. The anode circuit thus consists virtually of a small inductance in series with R_a, and the impedance of this circuit will now be considered to be sensibly that of R_a.

(*f*) *The determination of the mutual inductance between the reaction and primary.*—It is now necessary to determine the value of the mutual inductance at various settings of the reaction coil. A known high-frequency current at a frequency of 300 000 p.p.s. was passed through the reaction coil, and the open-circuit E.M.F. of the untuned primary was determined by means of a calibrated amplifier. The values of M and the coefficient of coupling so obtained are shown in Fig. 19. The relationship between M and the angular position of the coils is very nearly a sine relationship, as would be expected, but the law varies with different primary coils. The maximum coupling is only 32 per cent.

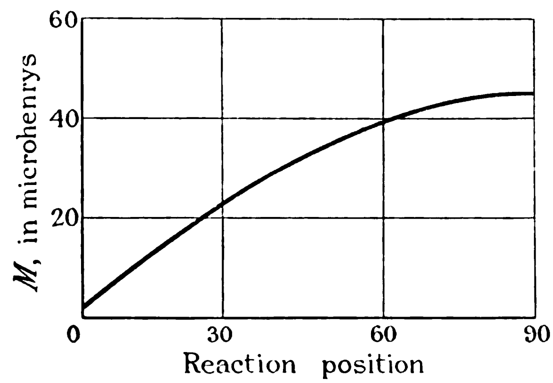


FIG. 19.—Experimental determination of M: stud 2.

From Fig. 18 we obtain the following relationships

$$E_b = \omega M I_a$$
$$I_a = uE_c/Z_a$$

where u is the voltage factor of the tube, and

$$Z_a = \sqrt{[R_2^2 + (1/\omega C_2)]^2}$$
$$\Delta R_1 I = E_b \sin\beta$$
$$= \omega M I_a \cos(\theta + \lambda)$$
$$= \frac{\omega M u E_c}{Z_a} \cos(\theta + \lambda)$$
$$= \frac{\omega M u I_1 Z}{Z_a} \cos(\theta + \lambda)$$
$$\therefore \Delta R_1 = \omega M u \frac{I_1}{I} \frac{Z}{Z_a} \cos(\theta + \lambda)$$

Now $$\frac{\sin\theta}{I_1} = \frac{\sin\phi}{I} = \frac{\cos\phi_1}{I}$$

$$\therefore \frac{I_1}{I} = \frac{\sin\theta}{\cos\phi_1}$$
$$\therefore \Delta R_1 = \frac{\omega M u Z}{Z_a} \frac{\sin\theta}{\cos\phi_1} \cos(\theta + \lambda)$$

Now $\cos(\theta + \lambda) \doteq 1$, $\cos\phi_1 = \dfrac{R_1}{Z}$ and $\tan\theta \doteq \sin\theta$

$$\therefore \Delta R_1 = \frac{\omega M u Z}{Z_a} \cdot \frac{\tan\theta}{R_1} Z$$

and
$$\tan\theta \doteqdot \frac{\Delta R}{\omega L}$$
$$\therefore \Delta R_1 = \frac{\omega M u Z \Delta R Z}{Z_a R_1 \omega L} = \frac{M u Z^2 \Delta R}{Z_a R_1 L}$$

From Fig. 14 (reaction = 10) we get $M = 6 \cdot 12\ \mu$H, where

$Z_a = 13\ 000$ ohms (determined experimentally)
$u = 4 \cdot 92$ (determined experimentally)
$Z = R_1 + j/(\omega C_1)$

where $R_1 = 20\ 800$ ohms and $C_1 = 9 \cdot 9\ \mu\mu$F
$$L = 126\ \mu\text{H}$$

The experimental determination gave 10 μH.

Assuming the ratio of changes in M given by experiment, theoretical curves for each reaction position were obtained and are shown for two values of L in Figs. 14 and 15. The agreement shows how nearly the experimental results agree with the theoretical treatment. The tailing-off of each curve when near oscillation is due to unstable amplifier conditions. The reason for the 40 per cent error between the measured and calculated values of M can be roughly explained, since in the measuring case the field is due only to the current in the mutual coil, whereas when the actual measurements were taken the mutual inductance formed part of a complex field generated at a considerable distance from the coils, and in addition the primary current would seriously modify the field form. The amplifier used consisted of a simple rectifier followed by two audio stages. The valves used were dull-emitters.

(*g*) *Summary of results.*—The amplifier may be considered as a resistance and capacity in series forming a load across the resonant system. The value of this capacity appears to be sensibly constant under all conditions, whereas the value of the resistance is dependent upon the value of the tuning inductance. The effects due to reaction can be expressed in terms of the known theoretical conditions.

Section 3. Distortion in Audio-Frequency Amplifiers.

(*a*) *Errors in measurements due to distorted waves.*—It has been shown that the output wave-form given by a 2-stage amplifier is nearly sinusoidal with very weak outputs, but if these amplification figures are extended to signals of about ½ mA (R.M.S. value) as in loud-speaker work, the voltage ratios have little value, for the wave is no longer sinusoidal.

It is generally assumed that if the valve is operated with no grid current and upon a linear part of its v_g/i_a characteristic, the output wave-form is sinusoidal. However, R.M.S. determinations of output have shown severe discrepancies, for the vibration galvanometer measures the amplification of the fundamental only, whereas the R.M.S. instrument gives a power determination including the energy in the harmonics that may be present.

It was soon noticed that the audible strength of a signal did not appear to be proportional to the R.M.S. value of current through the instrument. If harmonics were present, the same apparent sound intensity could be obtained with R.M.S. values of current but one-sixth of the current required if the wave was sinusoidal. Since the ultimate object of amplification tests is to indicate the relative strengths of the output *sound* intensity, it is necessary to establish the type of wave given by an amplifier under various conditions with a sinusoidal input.

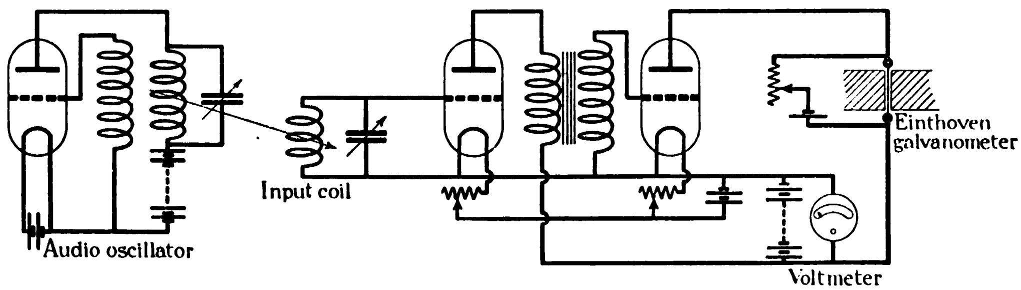


Fig. 20.

Great amplification can be obtained if reaction is pushed near its limit, but the distortion may be so great that the output signal may be of little value. For telegraphic signal reception the presence of the harmonics may be no disadvantage, but for telephonic reception it seems necessary to postulate a definite maximum departure from the sinusoidal form and to obtain the amplification under these conditions.

The 2-stage audio amplifier shown in Fig. 7 was used for the following investigations. The distortion was soon found to be so large that one transformer only was used. It may be stated that these transformers were known to be well above the average in performance.

(*b*) *Low-frequency determination of wave-form.*—At frequencies below 300 p.p.s. an Einthoven galvanometer was used as shown in Fig. 20. This galvanometer had a 14 μ copper string and the main d.c. anode current component was balanced out. Photographic results were obtained on a high-speed paper camera which ran at 6 m/sec. Records were obtained at low frequencies lying between 130 and 300 p.p.s. The output was about $0 \cdot 6$ mA (peak value) and showed a great departure from the sinusoidal form. The input was obtained from a filter circuit and when

photographed was found to be sinusoidal. The distortion is a minimum with large negative grid bias, but is still very appreciable. The decrement of the string was about 0·3 and its natural frequency about 800 p.p.s. Although it did not seriously affect the wave-forms obtained, the method could not be extended to the higher-frequency cases.

(*c*) *Higher-frequency determinations of wave-form.*—Since the amplification measurements were all performed at a frequency of 1 000 p.p.s., it was necessary to obtain a more complete series of results at that frequency. A cathode-ray oscillograph was used as the recording instrument and was connected as shown in Fig. 21. The difficulty when using this oscillograph is to obtain a large enough undistorted voltage replica of the weak anode-current changes. This, however, was effected by introducing a non-inductive resistance of 20 000 ohms into the anode circuit and suitably raising the high-

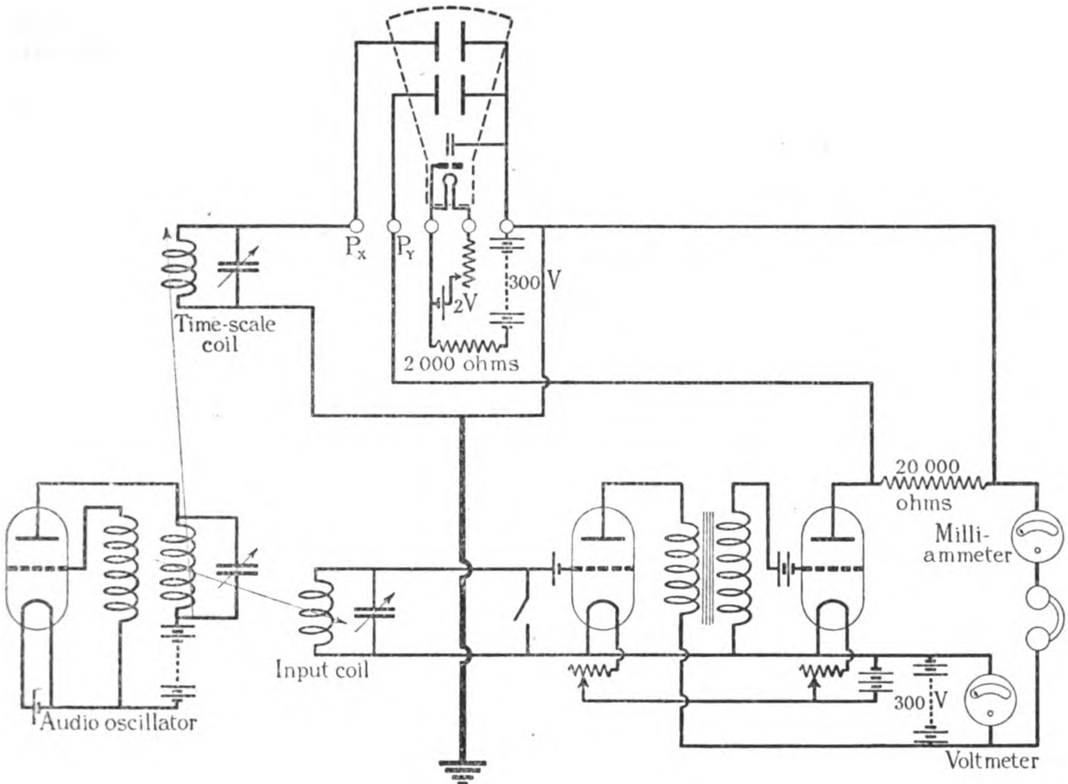


Fig. 21.

Table 3.

Curve number	R.M.S. current	First harmonic	Second harmonic	Third harmonic	Fourth harmonic	Fifth harmonic	Sixth harmonic	Form factor	Peak / Fundamental peak	Peak / R.M.S. peak	D.C. component of anode current in transformer primary
	mA	per cent	per cent	per cent	per cent	per cent	per cent				mA
1	0·6	100	54·6	23·0	—	—	—	1·135	1·37	1·23	2·3 (?)
2	0·6	100	48·0	16·5	—	—	—	—	—	—	1·7
3	0·6	100	42·2	9·5	0·5	0·5	—	1·22	1·4	1·32	1·12
4	0·345	100	55·8	29·1	10·0	2·5	10·0	1·24	2·08	1·75	3·4
5	0·645	100	31·2	10·4	—	—	—	1·18	1·57	1·34	2·83
6	0·276	100	16·8	9·2	—	—	—	1·17	1·25	1·21	2·83
7	0·181	100	16·5	8·6	—	—	—	1·17	1·2	1·2	2·83
8	0·507	100	1·2	2·25	4·4	3·6	1·75	1·125	1·0	1·04	2·25
9	0·407	100	6·3	2·8	—	—	—	1·13	1·06	1·065	2·25
10	0·203	100	6·25	8·3	—	—	—	1·127	1·14	1·09	2·25
11	0·654	100	17·5	3·7	7·9	2·0	2·0	1·28	1·21	1·19	2·25

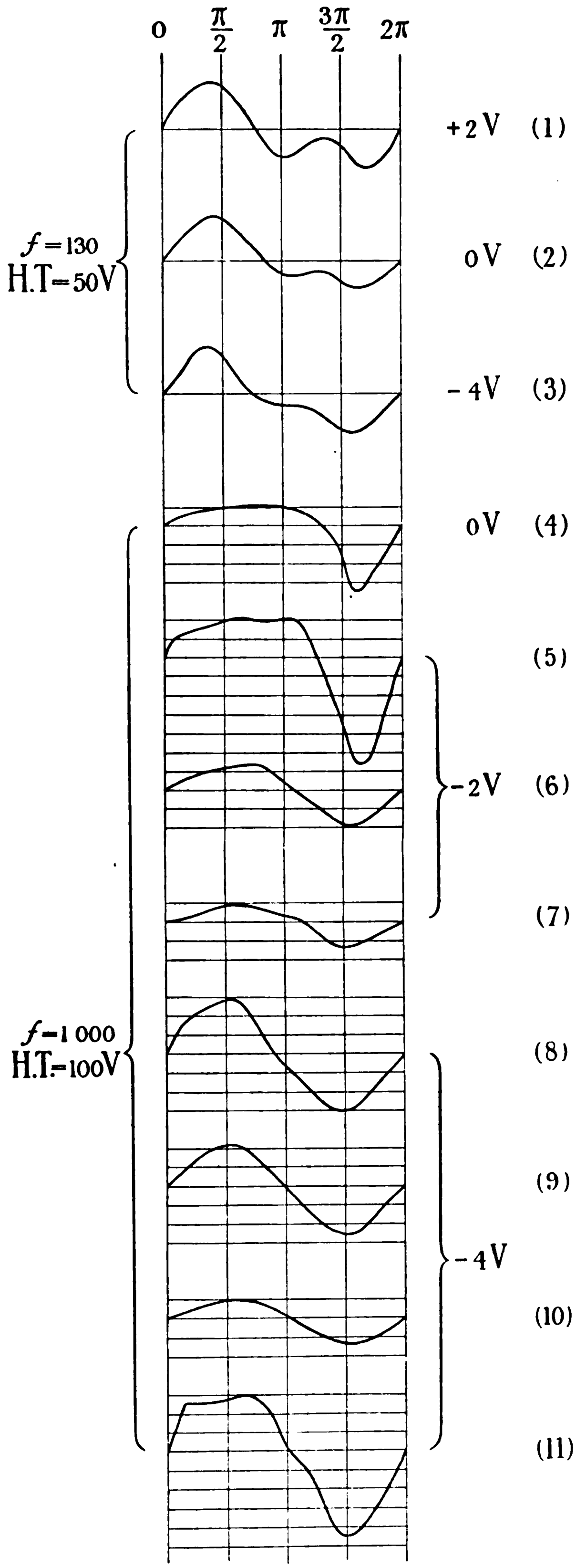


FIG. 22.

tension battery voltage until the plate voltage measured electrostatically was the same as before the insertion of the resistance. In this way a voltage of 10–15 was obtained for the overall changes, and the normal drop across the resistance was balanced out.

The input to the amplifier was the voltage across a tuned circuit very loosely coupled to the audio oscillator. The wave-form was found to be sinusoidal. The output across the anode resistance was taken to one pair of the cathode-ray tube plates, the other pair being connected across another tuned circuit loosely coupled to the same audio source. The magnitude of the input E.M.F. could be varied by adjusting the coupling of the input coil, and any convenient width of time scale can be obtained by adjusting the coupling of the time-scale coil. The sensitivity with 250 volts on the anode of the tube was about 1 mm scale deflection per volt.

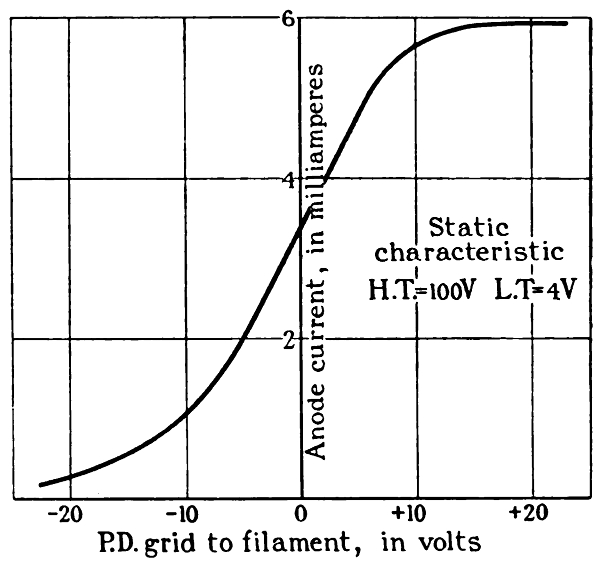


FIG. 23.

Photographic results were obtained by exposing bromide paper held against the screen. The Lissajous figures so obtained were analysed and the most important of the curves of wave-form deduced from them are shown in Fig. 22. The details of the Fourier analysis are given in Table 3.

(*d*) *Discussion of some observed cases.*—From a study of these curves it will be seen that the number and magnitude of the harmonics is considerable, and that the actual peak value may be as much as 75 per cent greater than the assumed peak value obtained from the R.M.S. value.

The grid-voltage variation is therefore in all these cases greater than would be given by a R.M.S. determination.

The output was never great enough to give a grid current in the cases with 2 or 4 volts negative bias on the grid, as seen from the static characteristic in Fig. 23. The following conclusions can be drawn from these results, remembering, however, that they must be considered only as provisional, considerably more

experimental work being necessary to confirm the general conclusions so far obtained.

(i) The effect of *increasing output* is to modify the wave-form seriously. In general, the harmonics increase in magnitude far more rapidly than the fundamental.

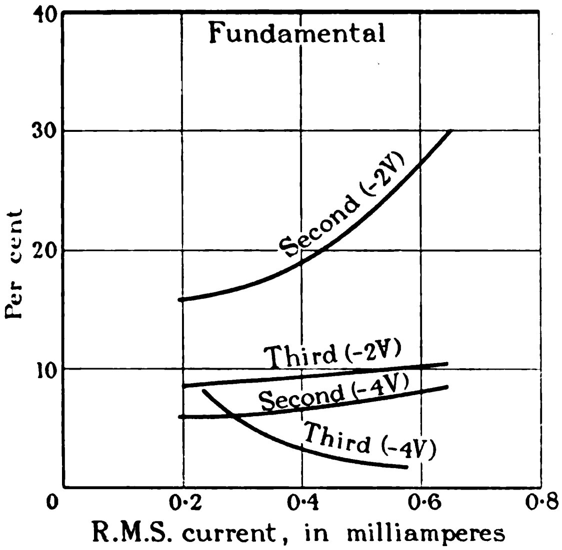


FIG. 24.—Percentage harmonics, with different grid potentials.

(ii) As the *frequency* is lowered, the distortion becomes much more serious. It is safe to say that at 150 p.p.s., the fundamental may be almost completely eclipsed by the harmonics with outputs of about 1 mA.

(iii) The effect of *negative grid bias* is to reduce the

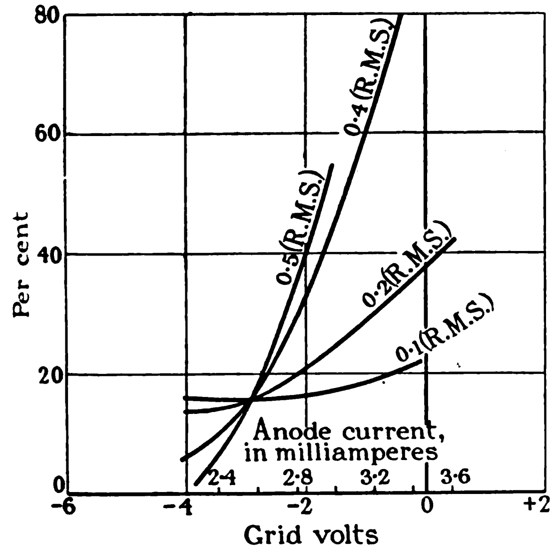


FIG. 25.—Ratio (Peak/Fundamental peak) expressed as a percentage greater than 1.

magnitude of the second and third harmonics and to introduce small harmonics of a higher order.

(iv) The *form factor* remains sensibly constant under most conditions.

(v) In curve 11 (Table 3), it will be seen that the rapid growth of the higher harmonics, the fourth, the fifth and the sixth, produces a critical distortion. This was noticed in many cases. The shape of the Lissajous figure quite appreciably changes with a very small increment of current beyond a given critical value.

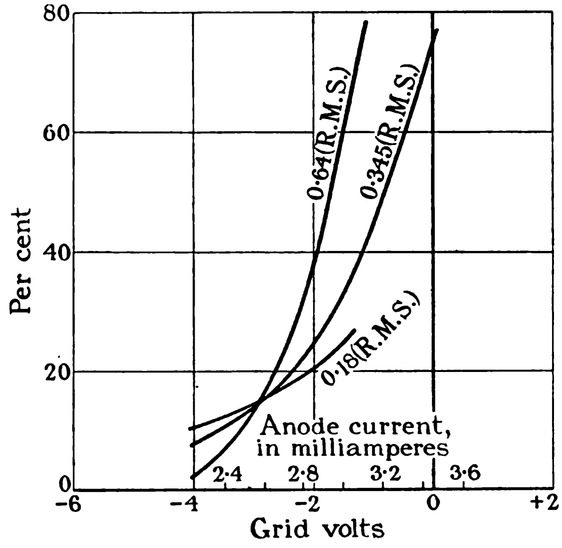


FIG. 26.—Ratio (Peak/R.M.S. peak) expressed as a percentage greater than 1.

The form factor and other ratios are seriously upset in this case, and do not fall into the final inferences with smaller outputs.

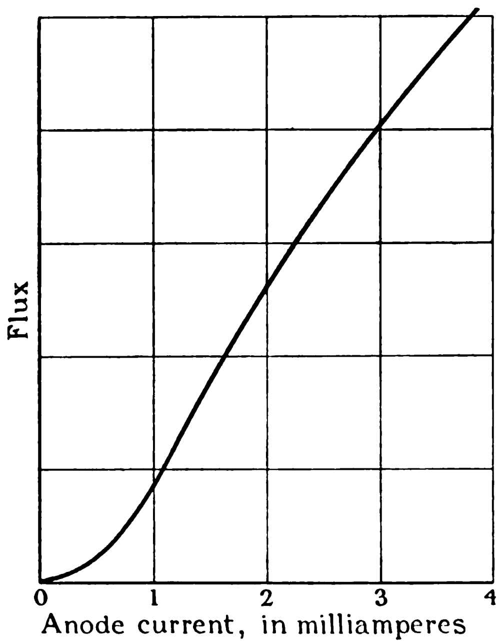


FIG. 27.

(vi) In Fig. 24 the percentages of the second and third harmonics are given for various outputs with different grid potentials. It will be seen that the rate of growth of the harmonics is much greater than that of the fundamental, thus demonstrating the rapid wave-

form change as the amplitude of the sinusoidal input is increased.

(vii) In Fig. 25 the ratio of the actual peak to the fundamental component peak is plotted for various output currents and mean grid potentials and is expressed as a percentage greater than unity. These curves all intersect at a point corresponding to a mean negative grid potential of 2·9 volts. This means that the wave-form is *not altered* by increasing the magnitude of the output, and this condition is valid only at this point.

Further, there is a *definite distortion* leading to an error of 18 per cent *which apparently cannot be removed by reducing the signal amplitude.*

(viii) The ratio of the actual peak value to the peak of a sine wave of the same R.M.S. value is plotted in Fig. 26, from which a precisely similar result is obtained at the same mean grid-voltage condition. It seems probable that this condition is one defined by the normal d.c. anode-current component in the primary of the transformer rather than any loading effect on the secondary, due to grid-filament impedance, which will be very large in all the cases we have considered.

This grid voltage corresponds to 2·6 mA primary current. In Section 1 it has been shown that the transformer voltage ratio is materially affected by the normal d.c. anode current, thus supporting this opinion. The shape of the *B–H* curve for the transformer is shown in Fig. 27, from which it will be seen that the polarizing flux brings the normal working point just at the beginning of the saturation bend. It is not easy, however, to observe any definite properties at this point.

(*e*) *Summary of results.*—It is apparent that the error between an R.M.S. determination of output and a fundamental wave determination as given by a resonant instrument may be often as much as 20 per cent. Further, the grid variation is much in excess of the theoretical as given by an R.M.S. measurement.

The general observations point to peak values giving the chief measure of output sound effect upon the human ear, and if this can be established it is clear that much modification will be necessary in our measurements of signal intensity.

These investigations were carried out for the Radio Research Board under the Department of Scientific and Industrial Research, and the author wishes to acknowledge his indebtedness to Sub-Committee D1 of the Board for their useful advice throughout the experiments.

He also wishes to acknowledge his indebtedness to Mr. J. Hollingworth, M.A., B.Sc., for his valuable co-operation in the early part of the work, to Dr. R. L. Smith-Rose, M.Sc., for much useful advice and assistance, and to his assistant, Mr. G. Warren, for his valuable aid in all the latter portion of the work.

Discussion before the Wireless Section, 2 December, 1925.

Prof. C. L. Fortescue: The use of the vibration galvanometer in the measurements described in Section 1 of the paper suggests that the amplitude of the output is much greater than that required for reception by telephone. A method of measurement more nearly equivalent to the ordinary telephone receiver will be necessary if the properties of the amplifier are to be investigated down to outputs as small as that of a just-audible signal. The observed increase of magnification with decrease of output amplitude is no doubt due, as suggested by the author, to change of wave-form, and this confirms the view that the amplitudes at which the measurements have been made are rather high. For loud-speaker amplitudes the vibration galvanometer is no doubt quite suitable if its indications are properly interpreted. The author points out in Section 2 the difficulties arising from the disturbance of the amplifier by changes of the geometric form of the input circuit, but in Section 1 he appears to have taken no precautions to avoid inserting switches in the "high tension" side of the apparatus used for applying the small voltage to the amplifier input terminals. It seems likely that capacity effects may have been appreciable and that they may explain the differences in the behaviour of amplifiers of apparently identical construction. The screening arrangements, also, appear to have been inadequate and the re-designed testing apparatus mentioned by the author in reading the paper will be a great improvement though even now it is doubtful whether they are sufficiently complete. With regard to the three conclusions on page 261, the author should make quite clear under what conditions the first of them is applicable, as there is a general belief that with many forms of amplifier the reaction on the input circuit may change sign. The theoretical treatment given by the author assumes that the valve may be regarded as equivalent to a resistance in series with a capacity—both at the grid and the anode. This assumption neglects cross-capacity effects which are almost always of fundamental importance, and the observed fact that the resistance R_1 is found to vary from 20 000 to about 290 000 ohms for different values of the inductance in the input circuit seems to be directly attributable to this omission. For the same reason the author's vector treatment of the subject cannot be regarded as even approximately complete. Unfortunately the data given in the paper are not sufficient to enable the effects of cross-capacity to be computed for the apparatus in use but it would, no doubt, be possible for the author to investigate the effects. The wave-forms of output in Section 3 bear out the results obtained by other observers when the amplitudes are as great as the 10–15 volts given in the paper. Up to 5 volts and with frequencies of 1 000 there should be no serious distortion if the valves are suitable and suitably adjusted. It would appear that a great deal more work is required in connection with this part of the paper.

Mr. L. B. Turner: The behaviour of amplifiers is a subject which calls emphatically for exact measurements. Amplifiers of various types are in very common use and give very varied overall performances; confident but nevertheless meaningless or obscure statements about amplification and distortion are met on all sides;

and it is far from easy for even serious experimentalists to analyse quantitatively the phenomena they observe qualitatively. Consequently the report of an orderly and painstaking research such as that of the present paper should be given an eager welcome. The author has elected to make output measurements throughout at an acoustic frequency and employs a vibration galvanometer registering sensibly only the amplitude of the component of fundamental frequency. His method of acoustic 100 per cent modulation of the high-frequency input is ingenious. He states on page 256 that the modulation is readily adjusted to 100 per cent by the ear's recognition of the second harmonic of the modulating frequency when 100 per cent is exceeded. I should be glad if he would give an account of the method and observations by which he was able to establish the accuracy of this easy way of adjusting to 100 per cent modulation. The modulation method is inspired presumably by the desire to make as much as possible of his plant serve for both high-frequency and low-frequency amplifiers. Whilst I appreciate the value of the vibration galvanometer for the low-frequency amplifiers, it does not appeal to me as the best method for high-frequency amplifiers. It does not in any way discriminate between the fundamental and harmonics of the high-frequency output of the amplifier, since the 1 000-cycle current passed to the galvanometer is proportional to the square of the *virtual* value of the P.D. on the rectifier.* It is said on page 257 that "the discrepancies" (in high-frequency voltage amplification) "arising due to a neglect of the harmonics present may be, as shown later, very serious"; but this method cannot investigate these discrepancies. If virtual voltage, and not the fundamental component only, is to be dealt with, a Moullin thermionic voltmeter or its equivalent, without acoustic modulator or vibration galvanometer, seems to have everything to recommend it on the score of simplicity. The author is mistaken, I think, when he says (see page 254) that the valve rectifier is objectionable on account of large earth capacities. It is precisely as unobjectionable in this respect as his own "measuring valve" (Figs. 1 and 3), whose place it would take. If it is desired to take cognizance of the fundamental alone of the high-frequency input, a possible method would be to produce the acoustic frequency for the vibration galvanometer, not by the author's acoustic oscillator, but by a high-frequency oscillator used as a heterodyne. A few practical details in the apparatus call for comment. Fig. 2 is very puzzling to me. First, it is surely a very poorly designed current transformer whose ratio is so sensitive to change in the magnetic condition of the core; and in this connection I should like to ask why (as stated on page 255) the secondary of the transformer was given a resistance equal to the total resistance of the galvanometer. Secondly, how is it that the curve relating transformation ratio with the polarizing current in the primary is not symmetrical about zero current? In Fig. 3, the high-frequency potentiometer F is shown with two sliders, the right one of which is connected to earth. Motion of this slider thus changes the earthed point in the high-frequency transformer secondary circuit. This seems to invite errors, particularly as the transformer primaries are, surprisingly, connected in the non-earthed side of the radio oscillator A. Fig. 6 shows a rapid fall of amplification with increasing input. No details of this amplifier are given; and I venture to suggest that perhaps here, as elsewhere, not enough account has been taken of grid damping. Were all the grids of this amplifier adequately negative in potential? If not, there need be no mystery as to the cause of the inconstancy of amplification. The series of curves in Figs. 8–16 are very interesting, but it is not clear to what amplifier they refer. Was it the six-stage amplifier mentioned at the end of page 258 or some simpler arrangement, as seems rather to be implied in the paragraph on the theory of retroaction? Whatever it was, one would like to have full details of the amplifier under examination. The later portions of the paper deal with distortion in low-frequency amplifiers, and are full of interest. I venture to think the sources of distortion are not so hard to find as the author seems to suggest. He says (see page 264): "It is generally assumed that if the valve is operated with no grid current and upon a linear part of its v_g/i_a characteristic, the output wave-form is sinusoidal." I hope to be able to continue to assume this, except, of course, in the presence of unsuitably designed iron-cored chokes and transformers. I think that in some at least of tests 1 to 11 of Fig. 22 there *were* grid currents, and the straight-line region of the triode characteristics was *not* adhered to. In tests 1 to 3 the output current was 0·6 mA through a negligible impedance, so that (judging from Fig. 23) the grid amplitude was some 2 V to 3 V. This would produce asymmetric grid damping in tests 1 and 2, but not in 3. But the large magnetizing current in any ordinary amplifier transformer, when used at a frequency as low as the present 130 cycles per sec., may well be credited with the distortion here. In tests 4–11, which were at 1 000 cycles per sec., the iron effect was doubtless much less. But here a resistance of 20 000 ohms was inserted in the anode circuit, across which a P.D. of 10–15 V amplitude was produced. Fig. 23, unfortunately, does not show the amplification constant of the triode; but taking it as 5, I calculate that the grid amplitude would be 6 V when that of the anode was 15 V. This would produce severe grid current in all the tests, and in some would reduce the anode current to values dangerously near the curvilinear region. In conclusion, I think we often ask too much of the last triode on our low-frequency amplifiers. The anode joined to an ordinary room loud-speaker may easily suffer an amplitude of some 50 V, and its grid (say) 8 V: it should be fed with grid and anode voltages accordingly. If the author had been more generous with his grid and anode voltages—say − 8 V and + 150 V—we should, I think, have had more shapely curves in Fig. 22.

Mr. P. W. Willans: The author in Section 1 of the paper gives under heading (*a*) a summary of the practical difficulties of measuring voltage amplification, and outlines a few general methods of making this measurement. In the course of this summary he

* See E. B. Moullin and L. B. Turner: *Journal I.E.E.*, 1922, vol. 60, p. 706.

remarks that the output of the amplifier must be either determined or kept constant, and whatever method be adopted the output must be measured in some way. I am venturing to bring forward a general method which does not depend upon such a determination of output or upon its constancy, but only on a comparison between the output and input voltages of the amplifier. The basis is a null observation, and not only is a comparison between the scalar values of the input and output voltages obtained but also the phase angle between these voltages. The method of making the observation may conveniently be considered in relation to Fig. A.

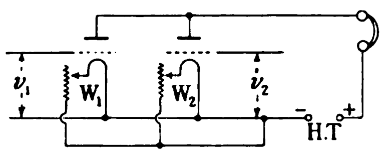


FIG. A.

Here W_1 and W_2 are two valves the filaments of which are controlled by separate rheostats. The anodes of these valves are connected in parallel through a pair of telephones and a source of high-tension current, and to the grids of the valves are applied alternating voltages v_1 and v_2, of the same frequency, from any source whatever. Then it is clear that if the valves have linear characteristics and identical mutual conductances, and if v_1 and v_2 are equal and in opposition of phase, then no sound will be heard in the telephones. In practice the valves can be so

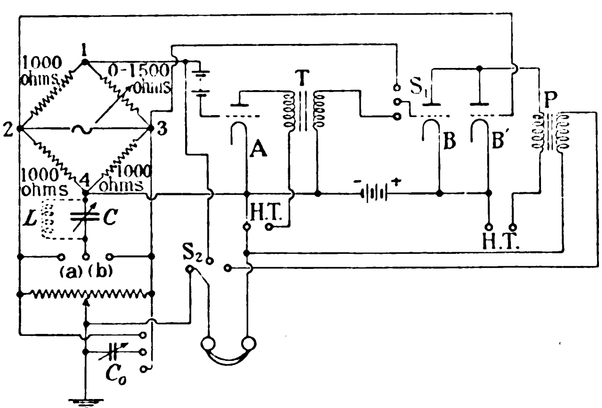


FIG. B.

adjusted that their mutual conductances are equal, by first arranging that the applied voltages are exactly equal and in opposition of phase and then adjusting the filament resistance of either W_1 or W_2 until no sound is heard in the telephones. If, then, one of these voltages, say v_1, be replaced by a voltage which varies in conformity with the adjustments of any measuring apparatus, we can bring this voltage into equality and opposition of phase with v_2 by effecting an extinction of sound in the telephones. It is worth noting that such an extinction will, in practice, only be attainable with the fundamental frequency of the applied voltages if their wave-forms are not identical. This is an advantage, since it helps to separate the effects of amplification on different frequencies. To apply a detecting device of this type to the measurement of voltage amplification it is convenient to use a bridge arrangement as illustrated in Fig. B. This shows the measurement of a single-stage transformer amplifier consisting of a valve A followed by an intervalve transformer T, and has been used mainly in the development and testing of audio-frequency intervalve transformers. The valves B and B′ correspond to the two valves shown in Fig. A, the anodes being connected in parallel and to the primary winding of a telephone transformer P. To the grid of the first valve is applied a fraction of the input voltage to a bridge which consists essentially of four arms, three of 1 000 ohms resistance and one, in general, slightly different from that value. Further, either of the ratio arms of the bridge can be shunted by a variable condenser. Referring to Fig. B, it will be seen that the condenser marked C can be connected either across the arm 2, 4, or across 3, 4; simultaneously we can throw the bridge out of balance in respect of resistance by adjustment of the arm 1, 3, which is variable from 0 to 1 500 ohms. The grid of the valve B′ is permanently connected to point 2 on the bridge, and the grid of B can be connected either to the output of the voltage amplifier or to the point 3 on the bridge, a switch S_1 being provided for this purpose. In order to effect the measurement we must first ensure that the mutual conductances of the valves B and B′ are the same. For this purpose we connect the grid of valve B to the point 3 on the bridge, balance the latter exactly, thus making the applied voltages equal and opposite, and by means of the filament resistances of these valves reduce the sound heard in the telephones to zero. Having made this adjustment we throw over the switch S_1 to the output of the voltage amplifier, and then displace the balance of the bridge until the output voltage is such that no sound is heard in the telephones. We then know that the output voltage of the transformer is equal and opposite to the voltage across the arm 2, 4 of the bridge and the input voltage to the amplifier is equal to the voltage across the diagonal 1, 4. Consequently the amplification ratio is equal and opposite to the ratio of the voltages across 2, 4, and 1, 4, respectively. These voltages can very readily be calculated. The resistance R_0 and the condenser C_0 constitute a Wagner earth connection, the arrangements being such that we can reduce to zero the voltage between the point 4 of the bridge and earth under all conditions of measurement. The resistance R_0 is of a total value of about 10 000 ohms, and the condenser C_0 consequently requires to be roughly one-tenth of the value of the capacity across the ratio arms, though it will deviate slightly from this value due to the stray capacities of batteries, etc., for which it is required to compensate. The switch S_2 enables the telephones to be connected to the bridge terminals direct, to the earth bridge, or to the output of the valves B and B′. In Fig. B an inductance L is shown as a dotted line across the condenser C. This may be used for the purposes of frequency measurement, the resonant circuit LC being shunted across either ratio arm and the condenser and variable resistance arm

being adjusted for exact balance of the bridge. It is important to note the conditions of measurement, namely, that there is, practically speaking, no impedance either in the input grid circuit or in the output anode circuit. In the first case the total impedance of the bridge is of the order of 1 000 ohms, which is negligible in comparison with the grid filament impedance of the valve at even fairly high frequencies. In the second case, since the adjustment is made in such a way that there is zero alternating current flowing through the telephone transformer windings, there is no alternating voltage on the plates of these valves and, in consequence, no retroactive effect on the amplifier. This reduces the conditions of operation to the simplest possible terms, and if it is required to observe the effect of input or output impedances these can be deliberately introduced in such a manner as not to interfere with the measuring apparatus. The calculation of the amplification ratio differs according to the position of the condenser C. Referring to Fig. C, which is a simplified diagram of the

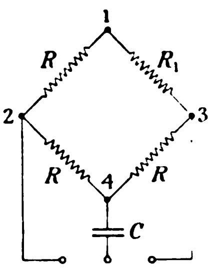


FIG. C.

bridge itself, if we denote the two positions of the switch as (a) and (b) and the voltages across 2, 4; 1, 4, etc., by v_{24}, v_{14}, etc., the formulæ can readily be established. Thus, for the switch in position (a)

$$\frac{v_{24}}{v_{14}} = \frac{R' + R}{R' - R - j\omega R^2C}.$$

And for the switch in position (b)

$$\frac{v_{24}}{v_{14}} = \frac{R' + R}{R' - \dfrac{R(1 - \omega^2R^2C^2)}{1 - \omega^4R^4C^4} + j\dfrac{\omega R^2C}{1 + \omega^2R^2C^2}}$$

ω being of course the angular frequency of the applied alternating voltage. In by far the greater number of practical cases the second formula can be simplified by neglecting $\omega^4R^4C^4$ in comparison with unity in the real term, and $\omega^2R^2C^2$ in comparison with unity in the imaginary term. We then have, as an approximate formula with the switch in position (b)

$$\frac{v_{24}}{v_{14}} = \frac{R' + R}{R' - R + \omega^2R^3C^2 + j\omega R^2C}$$

This method of measurement has been employed mainly on the investigation of audio-frequency intervalve transformers, where it has given results in excellent agreement with theory. I believe that work on multistage amplifiers has also been carried out on the same lines by other investigators, but I am not in possession of any results obtained. The advantages which I suggest are obtainable from the use of a general method of this type in measuring voltage amplification are threefold. First, in a number of cases it is possible to obtain more information regarding the performance of the amplifier under test if the vector ratio of output to input voltage is measured. This has certainly proved to be the case in respect of intervalve transformer work. Secondly, we are enabled to carry out measurements at very small output voltages, as, for example, ¼ volt or less at any frequency, without the use of calibrated apparatus. Lastly, the use by this method of a phase-splitting device as input makes it possible for a correction to be applied for the stray E.M.F. picked up by the amplifier, and this reduces the necessity for an elaborately screened source. In this last connection, referring again to Fig. B, we may disconnect the valve B′ in any manner and then reduce the output of the amplifier to zero by adjusting the bridge (with valve B connected to the amplifier) until no sound is heard in the telephones. If there is no stray E.M.F. picked up by the amplifier, the bridge will be exactly balanced under these conditions; if such an E.M.F. exists, a counter E.M.F. will be required at the input end of the amplifier and the bridge will then be unbalanced. We may then make a measurement of amplification as previously described and the input E.M.F. is reckoned as the vector difference of the *apparent* input E.M.F.'s in the two cases (the phase of the bridge E.M.F. v_{23} being counted as the same for both observations). The amplification ratio will then be corrected for the stray pick-up of the amplifier. The only condition for the success of this method is that v_{23} must be the same for the two observations, and this is substantially true in the case of measurements on powerful amplifiers, inasmuch as the bridge impedance varies only slightly for a small displacement of the balance.

Mr. J. Hollingworth: Having been associated with this work since its inception I do not propose to put forward any criticism of it, but rather to state briefly some of the early history of the investigation which occurred before, or very soon after, the author came to the laboratory. In this way, I think, the perspective of the whole can be more clearly seen. The matter arose out of a discussion in committee on two points. The first was that, whilst a great deal of mathematical work had been done on the subject of amplifiers, it had not in general been followed up by a consistent quantitative examination of any actual piece of apparatus in order to see whether the assumptions necessarily made during the mathematical work were justified in actual fact, and what values should be given to the actual constants which arose. Secondly, it was hoped to see what prospects there were for devising anything in the nature of routine tests for amplifiers in general, which would satisfy the usual conditions for such tests; namely that they should be capable of reasonably accurate repetition and at the same time should give a result really representing the behaviour of the amplifier under working conditions. The present paper is the commencement of an answer to these questions. With regard to the technical aspect, the vibration galvanometer was decided upon after considerable discussion in committee as offering

on the whole, in spite of its obvious limitations, the best method of attack. The other principal feature, the separation of the test into two parts, first the amplification of the instrument alone, and then the consideration of the effect upon its associated circuits, was derived from the work then being done upon signal-strength measuring apparatus, which had brought home very strongly the vital importance of the latter factor. This separation has been described as somewhat artificial, and doubts have been expressed as to its validity when applied to the complete apparatus; but both the results in this paper and those obtained by using the same principle in the signal-measuring apparatus during the past two years, seem to have answered this question satisfactorily. It can also be defended on theoretical grounds, but space does not permit of that. The only reservation is that there must be no stray inductive effects from the outside circuits to the intermediate circuits of the amplifier; if this occurs no real test is of course possible, as all results would be dependent on the chance arrangement of the outside circuits. Actually this has involved extremely elaborate screening, especially when an amplifier of five or six stages is under test, in spite of the fact that with this method it is no longer necessary to induce an accurately known E.M.F. into an oscillating circuit, for which the precautions would be even more severe. Considering the results obtained, the author has shown definitely, I think, that, if sufficient precautions are taken, results can be repeated to a degree of accuracy not often reached previously in this type of work; but that the precautions involved are very severe, and such small practical factors as a change of valves may have a considerable effect. He has also shown that the amplifying power, subject to these precautions, can be stated mathematically; but that it invariably involves reference to the associated circuits right back to the receiving aerial or coil. Again the results can only be expressed in the form of a vector impedance if they are to give numerical results in any way consistent with actual performance, so that it seems to follow that the results of any tests on an amplifier involving radio frequency can only be expressed in an elaborate mathematical form; and that any simplification of the mathematics would inevitably lead to results so different from those actually obtainable by experiment as to have very little value for purposes of classification. The use of the crystal circuit referred to in the paper for the determination of 100 per cent modulation is based on the following idea. Tests on the radio-frequency oscillator used showed that the curve between the high-tension voltage and radio-frequency current was, within the limits employed, a straight line which did not pass through the origin but cut off almost abruptly at a critical positive value of high-tension voltage. Consequently, if an audio-frequency E.M.F. were superimposed on the direct-current and so adjusted that the d.c. voltage exceeded the peak value of the audio-frequency voltage by this critical value, complete modulation should be obtained. At first all these voltages were measured directly in every case, but as this became very laborious when varying intensities were required, the crystal method was tried and was found successful. It is based on the idea that if the audio-frequency E.M.F. is too great, so that during part of the cycle the resultant E.M.F. becomes less than the critical value referred to above, the radio-frequency current ceases abruptly, and consequently the rectified wave-form will at once contain a second harmonic. Tests as described above and also with a cathode-ray oscillograph have shown that the accuracy is about 5 per cent, but it should be noted that the E.M.F.'s should be adjusted to the correct order before the crystal is used, as extreme forcing may bring in this harmonic again due to entirely different causes.

Major A. G. Lee: The chief point upon which I propose to touch is the measurement of the decrement of the input circuit when retroaction is present in the amplifier, the results of which are described in Figs. 8 to 16. The method adopted by the author was to use an input of constant amplitude, the frequency of which could be varied, and to plot the response in the input circuit of the amplifier in the form of a resonance curve. The response at the peak is assumed to be inversely proportional to the effective resistance of the circuit, and the response at any other portion of the curve is dependent upon the effective impedance of the circuit at the frequency of the point of the curve. From these details Equation (2), giving the decrement, is derived. Now, in a simple circuit without retroaction, the variation of impedance with frequency is given accurately by the expression $Z = \sqrt{\{R^2 + [\omega L - (1/\omega C)]^2\}}$. When retroaction is present, however, the effect of retroaction is to make both the resistance and reactance of the circuit a less simple function of the frequency. For example, the author mentions at the commencement of Section (2) that the effect of an amplifier upon the input circuit is to alter the tuning of the circuit. The subject has been dealt with in great detail by Bennett and Peters,* who show for a case somewhat similar to that of the author that both the resistance and reactance of a retroacted circuit are somewhat complicated functions of the frequency. It would seem, therefore, that the simple expression for the decrement in Equation (2) would not give the decrement accurately. A further point in connection with these measurements is that a strong input oscillator was used in order to get thermocouple readings in the input circuit. A question which arises in this case is whether the retroaction conditions of the amplifier were disturbed by this strong input, and whether the retroaction would have been the same with weak inputs. With strong inputs, for example, there is a danger of grid currents being produced at various points in the amplifier chain, and this would result in a reduction of the retroaction. The following are some minor points in the paper to which I should like to call attention. In Section 3 (*a*), paragraph 3, the statement is made that "the same apparent sound intensity could be obtained with R.M.S. values of current." I do not find this clear, and perhaps the author could amplify the statement. In the same Section, which deals with *audio*-frequency amplifiers, paragraph 4 refers to reaction being pushed near its limit, but, so far as I am aware, retroaction is not intentionally used in audio-frequency amplifiers.

* "Resistance Neutralization," *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 234.

Lieut.-Col. K. E. Edgeworth: The point in the paper that particularly interested me was the question of distortion in audio-frequency amplifiers. Some time ago I was trying to compare the input and output of a 2-stage amplifier, and I found that the musical note was so altered in character that a reasonably accurate comparison was out of the question. I formed the opinion that the distortion due to the production of harmonics was at least as important as the distortion due to unequal amplification. Only small currents were used and valve distortion was probably absent. When a valve is worked in such a manner that the grid is positive during a portion of the oscillation, there is a large variation in the input impedance of the valve, and the consequences of this change of impedance are increased by the use of transformers with a high transformer ratio. This effect has already been referred to by Mr. Turner. I believe that it is fairly well understood, and that it is generally accepted that the correct remedy is to employ a valve with large emission worked under suitable conditions. On the other hand there appears to be very little definite knowledge as to the distortion produced by the iron core of the transformer, and the best method of dealing with the trouble is by no means obvious. It would appear that several of the curves in Fig. 22 were taken under conditions which must involve distortion due to the valve as well as distortion due to the transformer, and it is difficult to separate the two effects. I suggest that research in the immediate future should be devoted to the investigation of the distortion produced by the transformer, this being the problem about which least is known. Experiments might be carried out with valves of high emission worked under such conditions that valve distortion is inappreciable. Such an arrangement would not only reduce the complexity of the effects to be interpreted but would enable larger currents to be used and would facilitate the question of measurement. There appears to be a tendency to assume that uniformity of amplification is the only condition which a transformer has to fulfil, whereas in fact transformers which give very uniform amplification may cause excessive distortion owing to a large production of harmonics. The best transformer is probably one which provides a compromise between the two conflicting sets of requirements. I feel very strongly that further knowledge in regard to transformer distortion would lead to a definite improvement in the reproduction of speech by audio-frequency amplifiers.

Mr. P. K. Turner: According to the paper very inconsistent results were obtained with the ordinary resistance-variation method of trying to find the input impedance of a valve, and these inconsistent results were ascribed largely to the fact that this method altered the geometry of the circuit; but I do not quite understand why it is that the substitution, say, of an inch or two of 47 S.W.G. Eureka wire in the exact location of an inch or two of 40 S.W.G. copper wire, should make a sufficiently important alteration in the circuit. It is standard practice, of course, to use exactly similar links, merely substituting Eureka wire for copper wire. Another difficulty is the fact that obviously the amplification of all high-frequency amplifiers is so greatly governed by retroaction effects. Twice in the paper the author brings out the point that the amplification on the high-frequency side appears to diminish as the input increases. A tendency towards a constant output has been found by an American writer. The statement on page 261 as to the effective resistance load not changing its sign with varying frequencies has already been mentioned. I take it that that refers purely and simply to a resistance-coupled amplifier. Of course it is generally recognized now that in all cases where some sort of tuned coupling is being used between valves that theory no longer holds good at all, and that whenever the anode circuit becomes reactive in the positive sense there is a tendency towards regeneration which may eventually lead to oscillation. Another point which has already been admirably dealt with is that, with the large distortion shown in experiments on audio-frequency amplification, the author has hardly been fair to his own circuit. Noting the characteristics shown in Fig. 23 at 100 volts, and comparing them with the grid inputs and R.M.S. currents produced in Fig. 22 (though the grid characteristic of that valve is on rather a small scale), it appeared to me obvious that the larger input could not be dealt with even by working the valve down on the lower portion of its curve by increasing the grid bias. The saturation current of this valve is of the order of 6 mA, and for swings of the amount given, as far as I can make out from rough measurements from the curves and Table 3, one would need a saturation current of 12 mA and a considerably lengthened curve before one could hope to get distortionless amplification.

(*Communicated*): Since the date of the meeting I have looked further into the matter of measuring input impedance and find some interesting points: (1) If the effect of reaction can be represented as simply a change in the input resistance of the first valve, without the introduction of a reaction E.M.F. into the tuned input circuit, then there is no difficulty. (2) If the effect of reaction can be represented by an E.M.F. (a function of the input voltage), then *if* this E.M.F. is in phase with the input E.M.F. the resistance-variation method may be modified to function, but the reaction variation method will not be satisfactory. If, in addition, the reaction E.M.F. is proportional to the input E.M.F., the ordinary resistance-variation method will suffice. (3) If the reaction E.M.F. is *not* in phase with the input E.M.F., then all the usual methods fail. The analysis on which these rather sweeping statements are made is quite simple and is merely omitted to save space.

Dr. R. L. Smith-Rose: I should like to take this opportunity of justifying the attitude which the National Physical Laboratory has had to adopt in regard to the testing of commercial wireless receiving sets. From time to time we are asked to carry out tests not only of amplifiers of high or low frequency, but also of complete receiving sets. We are requested to give some sort of certificate of merit of performance of the instrument. I think that the present paper, and also the discussion thereon, has emphasized the great difficulties there are in the way of obtaining consistent results in dealing with the amplifier alone, without adding receiving circuits to the front end of it, as would be the case in the complete receiving set.

The National Physical Laboratory has a reputation to maintain, and in the absence of any consistent method of measuring the various factors which it is necessary to measure in the receiver, we have had to confess that we do not know how to test these receivers so as to give some satisfactory certificate of merit of performance of the instrument. The paper shows, however, that an investigation has been commenced with a view partly, at any rate, to arriving at some satisfactory method of testing a receiving set. In view of Prof. Fortescue's remarks I feel that some explanation is necessary in regard to the screening that has been adopted recently, more particularly since I have been partly responsible for the screening methods adopted. I showed some time ago that in order to get complete screening of a radio-frequency field it was necessary to use tin-plate, and to solder up all joints round about the lid of the box in which the instrument to be screened was located. As that was, of course, very impracticable, methods of partial screening have been adopted, and a way has been discovered of fitting on lids to make adequate contact round the side. In continuing this work Mr. Barfield showed that wire netting gives moderately good screening for many purposes, provided care is taken to use netting of a fairly small mesh, and also to bond over all the joints. He also showed that the field inside a 1 in. mesh wire netting screen could be reduced to something like 4 per cent of what it is outside at wave-lengths of from 500 to 7 000 metres. In discussing what we should do in regard to putting these amplifiers in screens, we considered first of all the question of making big tin boxes, i.e. boxes large enough to crawl about inside. But in view of the fact that the radio oscillator and all leads therefrom are already screened with tin-plate, it was considered that if the stray field were reduced to about 4 per cent of its original value, that would eliminate any error due to direct induction from the oscillator. I believe that the author's recent measurements on that particular point have justified the adoption of a whole-room screen of wire netting in place of a small-space screen of tin-plate. I was very interested in Mr. Willans's method of testing low-frequency amplifiers and hope to study that in more detail later. The ideal method of testing low-frequency amplifiers should, I think, be one in which telephone receivers could be dispensed with. It is very difficult to make good telephone measurements at and below 250 cycles per second, yet, as we all know, the characteristics of the amplifier are required at frequencies down to something like 50 cycles per second.

Mr. R. C. Clinker (*communicated*): In connection with the paper, and also with Mr. Willans's contribution to the discussion, it may be of interest to describe a method of measurement due to Mr. C. G. Garton and used in the laboratory of the British Thomson-Houston Co., Ltd. This method can be applied to the determination of the amplification ratio of a low-frequency amplifier of any usual number of stages. It is used regularly for obtaining the frequency/ratio curves of low-frequency transformers, and has proved simple and accurate. In Fig. D (from which some items are omitted for clearness), T is the transformer under test. Its characteristic is to be determined when working with valves V_1 and V_2. The principle employed is to balance the voltage output from the secondary S against the drop across a known resistance R_2 which is placed in series with R_1 and carries a current measured by A. As the secondary voltage is out of phase with the drop across R_2, a mutual inductance M is inserted to provide a quadrature component and give a balance. Valve V_2 has its grid negatively biased, and serves as amplifier for headphones, H. A known audio-frequency voltage from source G is applied to the grid of V_1 by the drop across R_1. When a balance is obtained, the total amplification of one stage, consisting of valve V_1 and transformer T, is equal to $[(R_1 + R_2)^2 + M^2]/R_1$, and the tangent of the phase angle is $pM/(R_1 + R_2)$, where $p = 2\pi f$. For low frequencies a vibration galvanometer may be substituted for H, and a condenser shunted across R_1 for M. Section 3 of the paper shows some distortion effects obtained with the particular valve

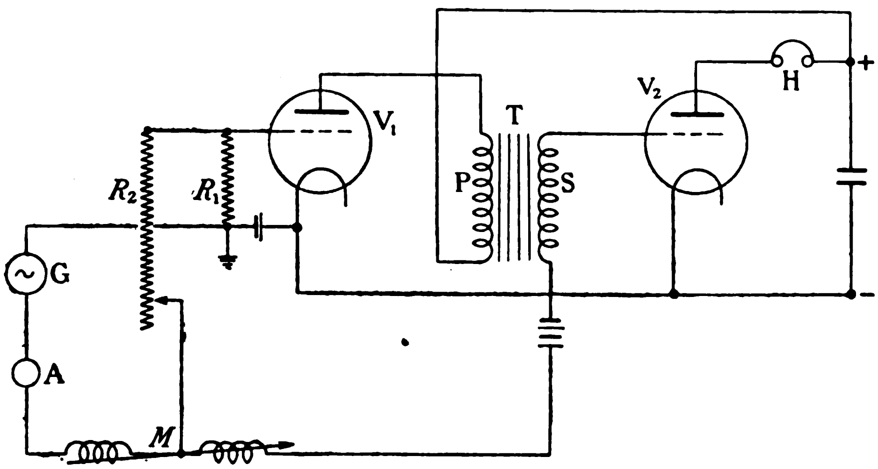


FIG. D.—Method of measurement of low-frequency amplification.

and transformer used, but although a curve is plotted in Fig. 23 no indication of the value of anode impedance of the valve is given. It would seem, however, that as distortion increased rapidly with the lowering of the frequency, the impedance of the valve must have been high in comparison with that of the transformer primary.

Mr. K. Sreenivasan (*communicated*): After everything is taken into consideration, the galvanometer method of measurement is decidedly superior to the telephone method from considerations of accuracy and sensitivity. Perhaps some simplification in the circuit and the apparatus used could be secured by either of the two following modifications: (*a*) Instead of using an audio oscillator for modulation purposes, a rotating contact breaker (or commutator) inserted in the oscillating circuit of the radio-frequency oscillator and driven at any required speed by a motor would do away with any necessity for the crystal circuit in order to detect the presence of harmonics. In this case an ordinary d.c. microammeter or galvanometer of the required sensitiveness will replace the vibration galvanometer. As the author remarks, a d.c. instrument keeps its calibration far steadier than a vibration galvanometer. (*b*) If an audio oscillator is indispensable, it would be a good plan to adopt a tuning-fork generator with the necessary arrangements in the output circuit. In this case a small 6-volt battery is all that is necessary. A tuning-fork generator not only works far more steadily than a tube oscillator, but is also remarkably free from harmonics, which are generally sources of trouble. The output will then be of constant frequency of great steadiness. The curve for the voltage amplification of a six-stage capacity-resistance amplifier is obviously obtained without any reaction introduced in the circuit. The average maximum amplification per stage comes to about 3·2, which is rather low. In view of the difficulties in working a resistance-capacity amplifier of more than four stages without self-oscillation, it appears to me that any steadying arrangements in this connection will reduce, more or less seriously, the individual, and so the overall, voltage amplification. It would be of some interest to know the amplification of a 2-, 3- and 4-stage resistance-capacity amplifier in order to have some idea of the fall in amplification per stage with an increase in the number of stages. Another aspect of resistance-capacity amplifiers about which one wishes to have more information is their behaviour with capacity reaction, say, between the grid of the first tube and the anode of the second, third or fourth tube. In a case like this it will naturally be difficult to reconcile experimental results with theoretically obtained values. The author's remarks in Section 2 regarding the resistance-variation method are very interesting. Experiments conducted in the Radio Laboratory at the Indian Institute of Science, Bangalore, with this method have given reasonably consistent results, variations from 5 per cent to 20 per cent being common, and 100 per cent extremely rare. These extreme variations were attributed to errors in reading the instruments. The resonance method, though very accurate, seems to be cumbersome and rather elaborate. I do not understand what "Reaction = 20," "Reaction = 30," etc., mean. Do these stand for any definite quantities or do they merely indicate the dial readings of the reaction coil? I should like to know if it was found necessary to adopt any system of shielding in order to avoid interference due to other radio or audio sources in the neighbourhood. This question arises because the author has used inputs of the order of those generally met with in reception. The adoption of the tuning-fork generator in the distortion experiments would have been of great advantage with regard to purity of wave-form. As a result of this investigation, I would ask the author if he can suggest any further remedies in minimizing the effects due to distortion. In the case of an amplification system consisting of a high-frequency amplifier, a detector and a low-frequency amplifier, how are the distorting effects due to the three individual portions related to the overall distortion? It is to be hoped that the author will give us later, comparative figures of the best performances of amplifiers of all the three types for a good range of frequencies. These would be extremely valuable to all interested in the design and building up of efficient and reliable amplifiers.

Mr. H. A. Thomas (*in reply*): With reference to the remarks of Prof. Fortescue, I would point out that the vibration galvanometer is capable of measuring an output of 6 μA, which is the current value for a medium telephone signal. The sensitivity range of this instrument is in fact that of weak telephone signals, and the galvanometer cannot be used for strong signals unless it is heavily shunted. I know of no other instrument which could be used for current measurement below 1 μA under the existing conditions.

In Section 2 I refer to the detrimental effect produced by inserting switching arrangements in the tuned input circuit, but in Section 1 there is no input circuit and the switches are permissible, as we are merely applying a small, known voltage to the amplifier input directly. Capacity effects have been calculated for this case and have been found negligible, as all leads are most carefully spaced. The screening methods adopted have been adequately defended by Dr. Smith-Rose, whose remarks answer the points raised.

The conclusions arrived at on page 261 are only meant to apply to the special case under investigation. In the absence of further comparative information it is not possible to extend these conclusions to other cases. In this particular case the observed results can be expressed mathematically if the amplifier input circuit is considered as a condenser and resistance in series, the chief merit of this conception of the input impedance being that the capacity component appears to remain sensibly constant under all conditions.

Mr. L. B. Turner asks for a more detailed account of the method of determining audibly the completely modulated condition for radio injection. I would refer him to Mr. Hollingworth, who has already given a statement of the method.

The minimum high-frequency output which can be measured by the use of the rectifier, audio amplifier and vibration galvanometer is 5 mV, taking the maximum sensitivity of the vibration galvanometer as 10 μA. If a thermionic tube voltmeter were used, the maximum

sensitivity would need to be 5 mV, and this could be obtained with a balanced pointer instrument in the anode circuit. However, I do not see how this method has any advantages, since it will only give R.M.S. values, and will not help in the determination of the amplification of the fundamental alone. A high-frequency resonance instrument or cathode-ray oscillograph is necessary for this purpose.

I think that the measurement of coupling values and currents would be so indirect that a heterodyne method of obtaining an audio output would give little accuracy. The frequency of both the injecting radio source and the heterodyne would have to be perfectly constant to give a constant-frequency beat note, thus requiring fork-driven circuits. However, since the resonant frequency of the vibration galvanometer is constantly changing, and is difficult to keep in adjustment, the audio source is very slightly variable to allow the galvanometer resonance condition to be tuned to. With constant oscillator and heterodyne the output beat note is inflexible in frequency, and thus the galvanometer would require adjustment for every reading.

I admit that the current transformer used is not a particularly good one, although the reason is not easy to find, as the iron section is large. The curve shown in Fig. 2 is merely given as the ratio calibration of the particular transformer used.

I wish to thank Mr. Turner for his helpful suggestion concerning the potentiometer and the current transformers. Small errors have been observable in this transformer, and the removal of the primary winding from the high-potential end of the oscillator has given greater accuracy. As the screening methods are improved it is found unnecessary to earth any point, in which case the whole system is effectively screened.

The amplifier used to obtain the curve shown in Fig. 6 was of the 3-stage tuned-transformer type, using bright R valves and 100 volts high tension, and, as is usual with such an amplifier, the grids were connected to the negative end of the filament. Negative bias causes oscillation when several stages are coupled in cascade and tuned.

I wish to thank Mr. Hollingworth for his remarks, which materially help to give a clearer concept of the purpose of the work. He has also effectively given the reasons why the audible 100 per cent modulation determination is comparatively accurate.

I am glad the experience of Col. Edgeworth tallies so well with my own. I am pleased to say that I hope in the near future to progress along lines such as he suggests. Large valves will be used and special transformers of known constants adopted for the purpose of determining the production of harmonics by the iron core.

With reference to the remarks of Major Lee, the case given in the paper before the American Institute of Electrical Engineers by Bennett and Peters is not a parallel case to the one I have cited. In my case the grid is directly connected to the tuned circuit, and retroaction takes place from the anode circuit into this tuned circuit. Surely, however, the best reply I can give is that, since the resonance curves obtained gave the same value of decrement for all cases taken on the curve, these curves *do* represent the condition of a circuit which has a constant apparent resistance for small changes of frequency. If rapid changes in resistance and reactance values had occurred over a small change in frequency, the resonance curves could not have given one value only for the effective high-frequency resistance.

I would point out that the input voltage applied to the amplifier for these tests was of the order of 10 μV, the oscillator used being 15 ft. away from the tuned receiving circuit. A powerful oscillator was used only for the determination of the normal high-frequency resistance of the circuit without an amplifier, and thus the suggestion that grid currents existed can only apply to the case of the weak input. In this case there was a 3-volt negative bias on each valve and the last valve had an input of only 200 μV upon its grid.

In the advance copies of the paper there was a slight error in the text in Section 3 (*a*), paragraph 3. I have now altered this to read: "If harmonics were present, the same apparent sound intensity could be obtained with R.M.S. values of current but one-sixth of the current required if the wave was sinusoidal." In paragraph 4 of the same Section I mean to infer that with an amplification system consisting of a rectifier followed by audio stages, great amplification due to high-frequency retroaction can be obtained, but the distortion due to the overloading of the audio amplifier may be so great that the output signal is of little readable value.

Dr. Smith-Rose has adequately stated the position that the National Physical Laboratory must adopt regarding the testing of commercial radio goods. Until we can interpret the behaviour of an amplifier in terms that will be of immediate practical utility to the manufacturer, we do not feel justified in testing apparatus of this kind. He has also answered the questions raised by Prof. Fortescue in connection with the screening methods adopted. As a result of some recent tests it has been found that 96 per cent of the external field is eliminated at a wave-length of 350 m and 94 per cent at a wave-length of 10 000 m. When one considers that the main oscillator is efficiently screened in a completely lined metal box, reducing the field to about 10^{-4} or 10^{-5} of the original, I think it must be admitted that the screening, although not perfect, is quite sufficient for most purposes.

The reasons for abandoning the inserted-resistance method raised by Mr. P. K. Turner are dealt with in the paper. The effect of this inserted resistance is to modify the amplifier conditions. It would, of course, be possible to duplicate the mechanical shape in copper and then in resistance wire, if that were the only difficulty. However, since I know of no one who claims high accuracy for this method when applied to the measurement of the high-frequency resistance of a tuned circuit the resistance of which is partly neutralized by the retroaction of an amplifier, I felt justified in obtaining more accurate results by the resonance method which, although complicated, yielded very excellent and consistent results. The curves given for the load introduced by the amplifier apply only to the case of

a rectifier followed by audio stages. The question of the effect of high-frequency stages has not yet been dealt with. It is apparent from a perusal of Fig. 18 that the grid voltage vector E_c is *not* in phase with the retroacting E.M.F. E_b.

The remarks of Mr. Willans are more of the nature of a separate statement of a method of measuring stage amplification than a criticism of the paper. However, the method which he has given is not without interest.

I cannot see why screening the oscillator is deemed unnecessary. Surely induction effects between the two valves used cannot be separated from the actual amplification of the system. The output valve is not working under normal conditions. The secondary of the transformer has certainly the load due to the grid-filament impedance of a triode, but this triode has no output impedance and, as Miller has shown, the input impedance will be modified seriously by this departure from actual conditions.

The method is essentially limited by the sensitivity of the human ear to pick out zeros of the fundamental in the presence of harmonics. At low acoustic frequencies, e.g. those below 200, this is very difficult, as pointed out by Dr. Smith-Rose. I cannot see that the apparatus is simple. A bridge of the type shown is essentially a complex piece of apparatus. I feel that more care should be taken over the many leads with their capacity and inductive effects. He speaks of a $\frac{1}{4}$ volt as being a small output voltage. I personally consider this to be very large, my measurements rarely exceeding 5 mV on the output valve.

Mr. Clinker's remarks, like those of Mr. Willans, do not bear very definitely upon the main subject of the paper. He describes a method of measuring the stage amplification of one audio valve and transformer, and adds yet another method to the many already in use. I would point out first what is surely a mathematical error. The amplification of the stage must be

$$\{(R_1 + R_2)^2 + (\omega M)^2\}/R_1$$

and not $\{(R_1 + R_2)^2 + M^2\}/R_1$ as he gives it.

This method requires the calibration of a mutual inductance and two variable resistances and appears to be unduly complicated. The calibration of the mutual inductance over a wide range of frequencies is by no means a simple matter and the final result is dependent upon a zero telephone balance which at low frequencies gives a rather poor sensitivity. Finally, the last valve is not working under normal conditions, since there is no oscillating current in the anode circuit. If the amplifier is modified by the insertion of the suggested apparatus, the amplification figure will be sensibly different from the normal case of a loaded output and an absence of the measuring gear. It has been my experience that any insertion of measuring apparatus intermediate to the input and output terminals may completely modify the performance of any amplification system.

Whilst I appreciate the suggestions made by Mr. Sreenivasan, I feel that the modification suggested would lead to an unnecessary complication of the apparatus rather than a simplification. If the radio oscillations were chopped in the manner suggested, the resultant envelope wave-form of the modulated continuous-wave output would seriously depart from the original rectangular wave-form, and the d.c. instrument in the last stage of the amplifier would of course give the R.M.S. value of this wave. It would consequently be difficult to interpret the amplification, as the output wave-form would depend upon the number of stages used in the amplifier. Charging effects, time-lags, and transient starting and stopping conditions of the high-frequency oscillations would all tend to distort the original rectangular wave-form. I think that a tuning-fork arrangement for providing the audio modulation would not give the output required, especially in those cases where the audio oscillator is used to supply the input to a pure audio amplifier. A master control of the main oscillator could be arranged, operated by a self-maintained fork, but this constancy in frequency is not required for this class of work, as the vibration galvanometer itself does not preserve its resonant frequency accurately and the audio oscillator has to be slightly varied in frequency to tune to the galvanometer for every reading.

It must be remembered that the one oscillator is used for a dual purpose :—

(*a*) As a modulator for high-frequency injection.
(*b*) As the direct injecting agent for low-frequency injection.

I agree that the maximum permissible stage amplification before oscillation occurs falls as the number of high-frequency stages is increased. Unfortunately I have no comparative figures to give definitely, but I have not noticed that the first stages give a greater factor than the last. All seem to be equally affected.

The problem of intervalve coupling and its effect upon overall amplification is an exceedingly difficult one, which is to be more fully investigated in the near future.

The resonance method is admittedly more complicated than the inserted-resistance method, but is justified on the score of accuracy. It is possible to obtain an accuracy of 1 per cent with this method, and this is, as the speaker states, greater than the experimental accuracy of other methods.

"Reaction = 20," "Reaction = 30," etc., are meant to signify the settings of the reaction coil in terms of the particular scale used. The amplifier is completely screened in a special room, the radio oscillator is screened with metal plate, all leads are well spaced and screened in metal-lined trunks, and finally the measuring control panel itself is shortly to be enclosed in a large metal-gauze screen, thus forming the final link in a completely screened piece of apparatus.

It is early to consider remedies to minimize distortion in low-frequency amplifiers, the causes of such distortion being as yet an unsolved problem. When the causes are understood, methods of elimination will be considered. The distortion so far considered is entirely that occurring in the audio side of the amplifier.

A special cathode-ray oscillograph equipment, nearly completed, will examine the high-frequency distortion

produced. It has also been demonstrated recently that distortion takes place in the rectifier due to the modulated nature of the applied input.

I would point out in conclusion that the many combinations that require examination are such that the final statement of the observed results cannot be given until much more work has been done. Only by a careful examination of each case can a thorough understanding be obtained, and the results must of necessity be slow in appearing.

INSTITUTION NOTES.

Faraday Medal.

The Council have made the fifth award of the Faraday Medal to Colonel R. E. B. Crompton, C.B., Honorary Member and Past-President of the Institution.

North Midland Centre.

Mr. H. Cecil Fraser has been appointed Hon. Secretary of the North Midland Centre, to fill the vacancy caused by the death of Mr. J. D. Bailie.

Informal Meetings.

The Smoking Concert which was to have been held on the 15th March at the Engineers' Club has been cancelled by the Informal Meetings Committee.

The following Informal Meetings have been held :—

71st Informal Meeting (26th October, 1925).

Chairman : Mr. R. A. Chattock (President).

Subject of Discussion : "How can the Cost of Distribution be cheapened" (introduced by Mr. R. A. Chattock).

Speakers : Messrs. P. Rosling, W. Brown, A. F. Harmer, T. Rich, W. E. Rogers, G. H. Stevens, W. P. Fanghanel, H. Richardson, N. W. Prangnell, D. G. Hurlbatt, W. F. Andrews, E. S. Ritter, J. S. Rann, C. D. King, J. Coxon.

72nd Informal Meeting (9th November, 1925).

Chairman : Mr. A. H. Allen.

Subject of Discussion : "Modern Developments of Telephone Cables" (introduced by Mr. E. S. Ritter).

Speakers : Messrs. W. E. Twells, T. W. Riley, A. C. Rosen, W. Day, G. C. Marris, S. M. Catterson, J. Coxon, A. F. Harmer, F. Tremain, M. D. Hart, J. W. Wheeler, H. T. Werren, Major A. G. Lee, Mr. A. H. Allen.

73rd Informal Meeting (23rd November, 1925).

Chairman : Mr. J. Coxon.

Subject of Discussion : "The Testing of Large Electric Plant" (introduced by Mr. E. E. Tasker).

Speakers : Messrs. F. Creedy, M. D. Hart, W. E. Highfield, J. F. Shipley, W. E. Rogers, J. Coxon, J. R. Bedford, W. A. Erlebach, R. Samphier, A. Barraclough, W. J. Minton, R. D. Gifford, D.Sc., C. L. Lipman, D. G. Hurlbatt.

74th Informal Meeting (7th December, 1925).

Chairman : Mr. P. Dunsheath, O.B.E., M.A.

Subject of Discussion : "Design and Performance of Protective Relays" (introduced by Mr. C. L. Lipman).

Speakers : Messrs. R. D. Gifford, D.Sc., A. G. Hilling, F. E. Ockenden, J. F. Shipley, E. S. Ritter, G. N. Wright, F. H. Nalder, — Laws, H. S. Petch, H. Lloyd Williams, F. Pooley, P. Dunsheath, O.B.E., M.A., Col. K. Edgcumbe.

75th Informal Meeting (11th January, 1926).

Chairman : Mr. A. G. Hilling.

Subject of Discussion : "The Electrical Installation in the Rockefeller Building, University College" (introduced by Mr. W. C. Clinton, B.Sc.).

Speakers : Messrs. H. T. Young, J. R. Bedford, W. E. Rogers, G. C. Allingham, E. H. Freeman, C. L. Lipman.

76th Informal Meeting (25th January, 1926).

Chairman : Mr. C. L. Lipman.

Subject of Discussion : "Impressions of my Visit to America, mainly about Switchgear" (introduced by Mr. H. W. Clothier).

Speakers : Messrs. H. Trencham, M. D. Hart, A. F. Harmer, R. C. Andersen, — Ferguson, G. M. Davies, Col. K. Edgcumbe, Messrs. D. Kingsbury, C. L. Lipman.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 December, 1925–25 January, 1926 :—

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AN ALL-ELECTRIC HOUSE.

By Professor S. PARKER SMITH, D.Sc., Member.

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SUMMARY.

The scarcity of precise and detailed information on the several domestic applications of electricity encouraged the author to write a succinct account of the arrangements adopted in a 10-roomed house designed and built in Glasgow for all-electric working. In this house neither coal nor gas is used. The sections dealt with are :—

(1) Layout of house.
(2) Distribution board.
(3) Wiring.
(4) Bells.
(5) Lighting.
(6) Clothes-washing and drying.
(7) Cooking.
(8) Hot water.
(9) Ventilation.
(10) Heating.
(11) Running costs.
(12) Conclusions.

The total cost of 16 584 units used in one year's working was £43 8s. The consumption and costs are analysed for the several services.

In an Appendix, the results of a 4-roomed all-electric flat are given. The consumption for one year was 4 656 units and the total cost of energy was £14 18s.

INTRODUCTION.

In 1923, the author, being in need of a house in Glasgow, where the Corporation actively encourages the domestic use of electricity, seized the opportunity offered to build himself an all-electric house. The most noteworthy feature connected with this proposal, apart from details, was the adverse criticism which it elicited from the majority of electrical engineers with whom the scheme was discussed; so much so, that the carrying out of such an unpopular idea must be largely attributed to the obstinacy of one who thought that the time had arrived when a professor of electrical engineering ought to have enough faith in his convictions and calculations to put them to the test. Apart from doubts of critics as to cost, due in most cases to ignorance of the cost associated with the use of gas and coal, a coal fire for the sitting-room was almost universally advocated. The drudgery associated with the burning of coal in open fireplaces—such as removal of ashes and blackleading of grates—the pollution of the atmosphere, needless labour and waste, etc., in the eyes of many engineers seemed to be negligible compared with the romance of the coal fire. The layman, and particularly the laywoman, however, proved to be easier converts, especially where the domestic-servant problem was acute or where young children had to be considered. To the lay mind, the disposal of refuse—particularly garbage—seemed to be the main argument for retaining a coal fire. It was soon discovered, therefore, that the main objections to an all-electric house would be :—

(1) Excessive running cost.
(2) Absence of coal fire in sitting-room.
(3) Difficulty of disposing of refuse, mainly garbage, in the house.

It is hoped that this paper will show that none of these objections proved serious.

It is not intended here to do more than give a description of the layout of the house in question and a summary of one year's working. The calculations are all based on the tariffs of the Glasgow Corporation (which, by the way, also arranges for the hire of electric cookers and fires). Whilst thus limiting the scope of the paper to the author's own experience, it has to be remembered that there is nothing novel in the general problem of the use of electric appliances for domestic purposes, or in tariffs suitable for the domestic load.

In Glasgow the domestic consumer is offered the choice of two alternatives :—

(1) Energy at 4½d. per unit for *M* units and ¾d. per unit thereafter, where *M* is the estimated annual consumption for lighting and includes the consumer's share of capital and fixed charges.
(2) A two-part tariff consisting of a fixed charge to cover the consumer's share of capital and fixed charges, and ½d. per unit for all energy taken. The fixed charge appears to be about one-eighth of the rent, and in the author's case works out at £12 10s. per annum.

A simple calculation shows that domestic users will usually choose the latter alternative where heating and cooking loads predominate. For the author's house $M = 582$, and the two-part tariff led to a saving of £7 6s. 5d. in the first year's working. Compare also Figs. 10 (*a*) and 10 (*b*).

In passing, it may be pointed out that, even with favourable rates, the cost of an abundant supply of hot water might be considered unduly high, but it will be shown in the section on "Hot Water" how a satisfactory solution has been found.

Before considering the main points, such as heating, cooking, lighting, hot water, etc., a word may be said about capital cost. The house was built to be a home and not a showroom. This is an important point in determining the capital cost of an all-electric house, for in addition to the increased convenience obtainable with essential apparatus such as electric cookers, fires, etc., there are many available and possibly desirable appliances such as cleaners, warming pads, etc., which cannot be legitimately included under capital

cost. Even apart from appliances it is a difficult matter to determine accurately the effect of "electrifying" a house on the cost of construction, for it is not easy to analyse the installation costs. Suppose, for example, the house were wired and gas and coal were also to be used, a certain number of sockets for plugs would properly be included in a modern layout, and up to this point the cost of the installation of the all-electric house would be the same as for any other modern house of the same size. Unless, therefore, electricity be used for lighting only, any estimate of the effect of electrification on the cost must be necessarily rough.

After careful consideration, and taking into account that many appliances can be hired, the author is of the opinion that the cost of the house was 3 to 4 per cent higher than it would have been with coal (or coke), gas appliances and electric lighting. Whether there has been undue extravagance, the reader can judge for himself. It must, however, be remembered that the architect can effect many savings; for example, neither coal-house nor scullery is needed, nor is restriction placed on the design by the position of the flues, etc.

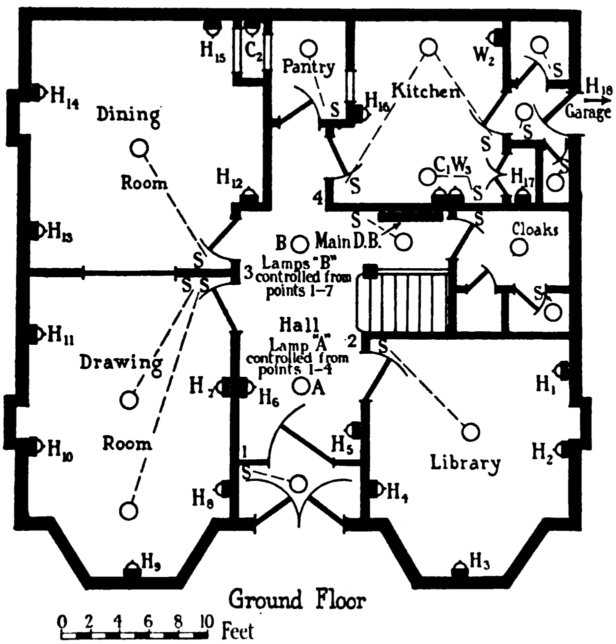

Fig. 1.

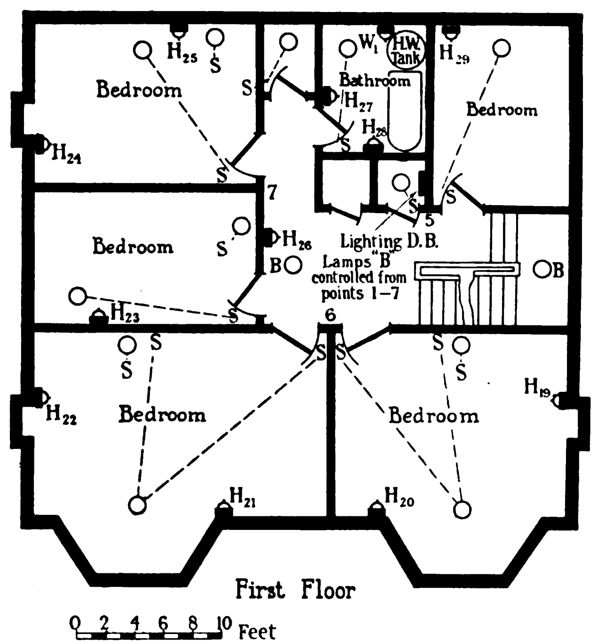

Fig. 2.

(1) Layout of House.

An idea of the layout can be obtained from the plans in Figs. 1, 2 and 3. The architect, Mr. J. Austen Laird of Glasgow, designed the house to meet the requirements of all-electric working, whilst the author was responsible for the electric layout. In passing, it may be mentioned that an all-electric house is essentially a case for co-operation between architect and engineer, for to obtain the best results the peculiar nature of electricity (just as in the case of gas or coal) must be consulted.

In all, there are 10 rooms—three reception-rooms and kitchen on the ground floor, five bedrooms on the first floor, and a large attic nursery. Below the ground floor there is a sloping space like a shallow cellar, 3 to 4 ft. high, which is accessible and is used for much of the ground-floor wiring. The floor dimensions of the rooms can be obtained from the figures; on the ground floor the rooms are 9 ft. 6 in. high, and on the first floor 9 ft. high.

From the enlarged plan of the kitchen in Fig. 3 it will be seen that there is no scullery or wash-house. No provision is made for coal storage, the only out-house being a garage.

It will be noted that there are three external chimney breasts; these are used for ventilation. By fitting grates and replacing the ventilators by chimney-pots, coal fires could be used—a feature which calls forth the approval of many critics of the all-electric idea. There are no mantelpieces or overmantels, but the fireplace recesses have been retained owing to the common practice of sitting round a fire. Since the only dirt, generally speaking, comes from outside (through the windows), the architect had a fairly free hand in determining fixings and decorations. The floors (on the ground flat) are polished and of hard wood, whilst the remaining woodwork is polished cedar.

(2) Distribution Board.

From Fig. 4 it will be seen that separate meters were installed for registering the respective consumptions for heating, hot water, cooking and lighting. These meters can be regarded as experimental and would not be needed for the ordinary consumer. The main meter is of the two-rate type and is actuated by a 40-day clock, so that the day and the night consumptions can be recorded separately; the purpose of this will be explained later. There are 31 heating circuits, and 5 circuits for cooking and hot water. Each of these circuits has its own fuses and goes to one point only, as indicated in

Figs. 1, 2 and 3, by H_1 to H_{17}, H_{19} to H_{29}, C_1, C_2, W_1, W_2 and W_3. (H_{18} is in the garage; H_{30} and H_{31} are in the attic nursery.) These points are 15-ampere wall sockets, with the exception of the cooker and the hot-water tank which are wired for 30 amperes. The lighting distribution board is fixed in the housemaid's closet on the first floor (Fig. 2) and feeds four circuits.

The main distribution board is placed in an accessible position between the hall and cloak-room, and the teak board and boxes accord well with the neighbouring woodwork, which is polished cedar.

(3) Wiring.

In general, the Wiring Regulations of the Institution were adhered to. Though screwed conduit appears to be favoured in Glasgow, the author decided that tough rubber sheathing (C.T.S.) was better for his purpose. With the large number of circuits throughout the house it is probable that C.T.S. was the simplest solution, and nothing has yet occurred to make the author believe that it was not also the cheapest and the best solution.

The supply is direct current at 250 volts, the positive and neutral being brought to the house.

The sizes of wire used are as follows :—

Cooker circuit (C_1)	7/·044 C.T.S. twin.
Hot-water circuit (W_1)	7/·044 C.T.S. twin.
Heating circuits (H_1 to H_{31}) ..	3/·036 C.T.S. twin.
Hot-water circuits (W_2 and W_3)	3/·036 C.T.S. twin.
Cooking circuit (C_2)	3/·036 C.T.S. twin.
Fan circuit	3/·036 C.T.S. twin.
Lighting circuits	3/·036 C.T.S. single.
Bell circuits	1/·044 C.T.S. single.

A 7/·036 bare stranded copper cable connects all sockets, etc., to earth.

Switch-sockets are used throughout. These are of the 15-ampere, 3-pin, flush pattern with a mechanical interlock to prevent the plug being removed with the switch on, or switching on before inserting the plug. With few exceptions all switch-sockets are inserted in the skirting board and the switches are arranged to be put on or off by the foot. The object in employing sockets all of the same size is to enable all fires and other appliances—kettle, iron, vacuum cleaner, etc.—to be used wherever desired. Against the objection to using, for example, a lamp standard on a circuit fused for 15 amperes, there is the advantage of convenience. Moreover, wherever there are several points per circuit, lamps and other appliances have often to work with liberally rated fuses.

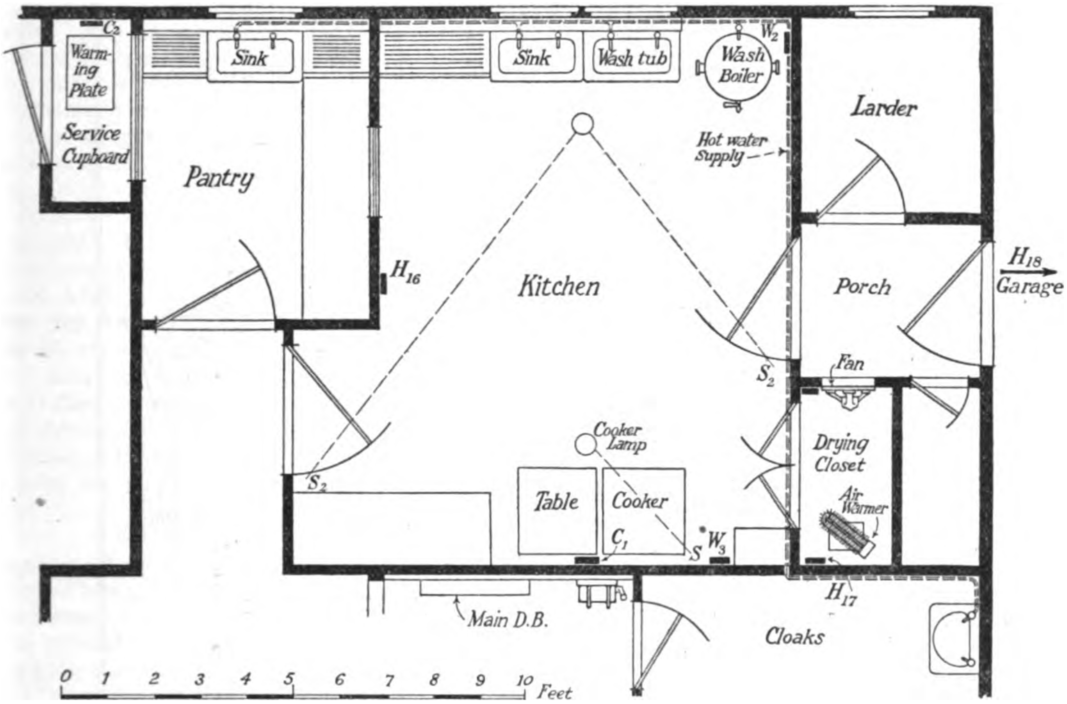

Fig. 3.—Enlarged plan of kitchen and services.

The number of points per room needs careful consideration. The author's experience has shown that in the living rooms 4 to 5 points per room are desirable. It is not unusual to have such a combination as the following in service in one room at the same time :—two fires, a desk lamp and a tea kettle; or a fire, a toaster, a coffee percolator and an egg boiler. In certain places it has been found convenient to duplicate some of the points by using a 15-ampere plug with a 5-ampere adapter.

(4) Bells.

In order to have the bell circuits as sound as the lighting and heating circuits, C.T.S. wire was also used. This may appear to be extravagant; but it is an advantage to have reliable bell circuits in an electrical engineer's house. In addition to an indicator, there are three bells—a deep-toned bell for the front door, a shrill-toned one for the side door, and a gong for the indoor pushes.

In important rooms there are bell-pushes near the door and near the fireplace.

(5) LIGHTING.

It will be seen from the costs in Table 3 that the charge for lighting works out at about nine shillings per quarter —consequently abundant lighting everywhere is permissible. Relatively, therefore, the cost of lamps is an important factor, and indeed this may be a case where under-running lamps (i.e. running lamps at less than the rated voltage) may be sound policy for the user.

Wherever it is desirable to operate a light from more than one point, suitable switching is provided. The hall light A can be operated from 4 points—vestibule door, kitchen and pantry, dining-room and drawing-room, library and foot of stairs. A second light B at the foot of the stairs is in the same circuit as the lights B on the half-landing and landing. In addition to controlling these 3 lights from the 4 points just mentioned for the hall light, they can also be controlled at 3 points on the first-floor landing. The convenience of being able to control the stair lights from 7 points can scarcely be

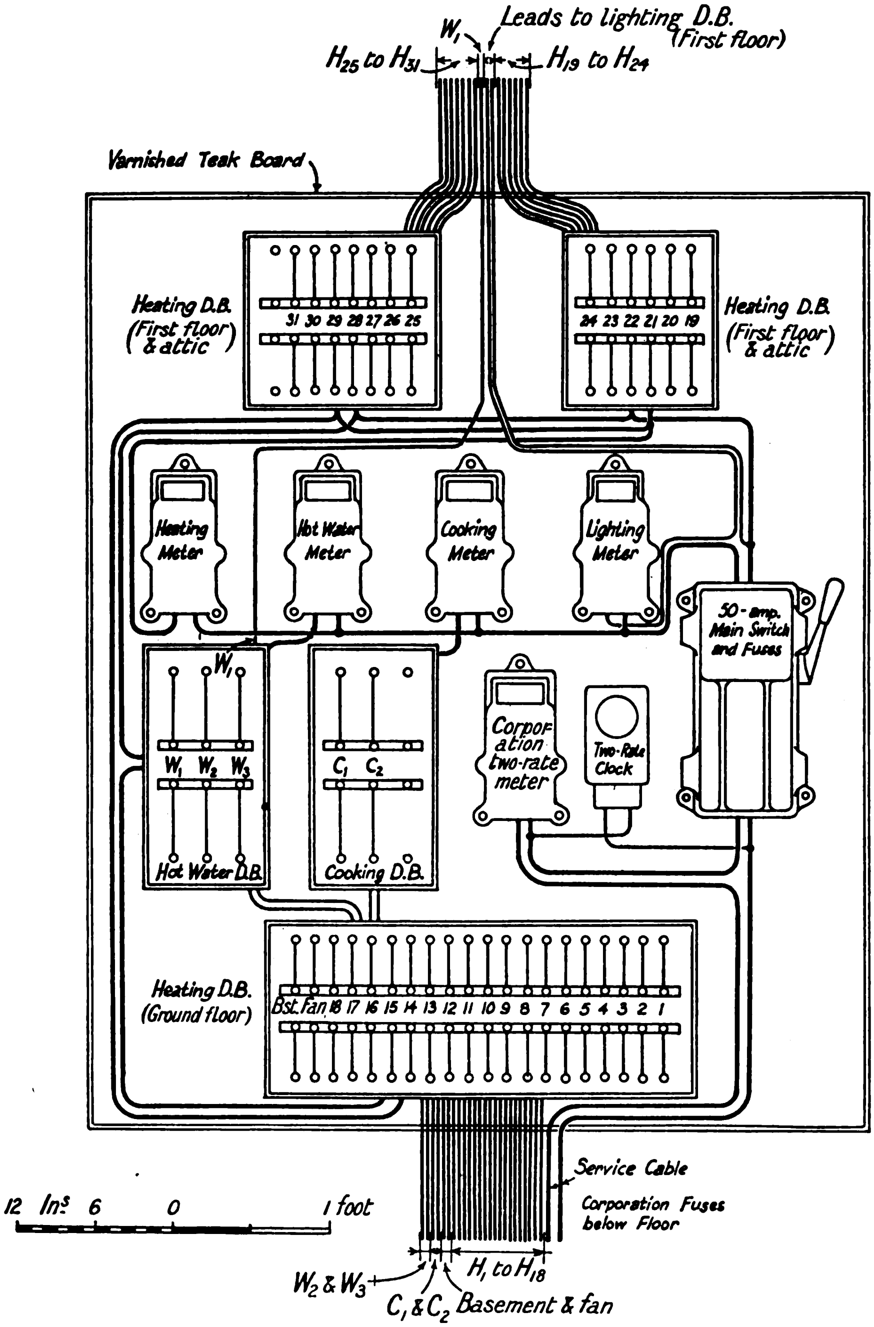

FIG. 4.—Main distribution board with experimental meters.

exaggerated. These control points are indicated in Figs. 1 and 2.

In the principal bedrooms, the dressing-table lights can be controlled from either the door or the bed, whilst an additional independent reading-lamp is placed over the bed.

In the kitchen an additional strong light is placed over the cooker and is controlled from a convenient point. All the switches are of the flush pattern, and exposed or unshaded filaments are avoided throughout the house.

(6) Clothes-washing and Drying.

In Glasgow a wash-tub is often fitted alongside the sink, and a small wringer with rubber rollers can be readily attached. Alongside the enamelled tub a wash-boiler of the percolator pattern has been placed (see Fig. 3). The loadings are 2 kW, 1 kW and ½ kW. Articles, after being soaped, are placed in this boiler, no preliminary scrubbing being necessary, as the washing is done by the continuous circulation of the boiling water. Unpleasant steaming is avoided by controlling the heat; and after bringing the water to the boil the process is usually completed in half an hour with the rotary switch on "low."

Drying facilities become essential in a wet climate. For this purpose, the drying-closet shown in Fig. 3 has been provided. The clothes are hung over 10 wooden rods, while an exhaust fan draws air from the space below the floor. On entering this closet the air passes over an air warmer of the convector type, rated at 1¼ kW. After an hour the dried clothes come out as fresh as if they had been hung out in sunshine. Not only is this drying closet a convenience at all times for sundry articles, but it is a vast improvement on the unsightly poles and pulleys often seen in kitchens.

(7) Cooking.

Electric cooking well merits the success it has gained. The absence of smell, smoke, dirt and fumes shows that many objectionable odours commonly associated with cooking are avoidable. Indeed it is probable that with electric cooking much less will be heard of the "nasty smell of cooking throughout the house." Smell there may be, but not the nasty smell which is so repugnant. Other merits of electric cooking rapidly discovered are simplicity in working and ease in obtaining good results. The thermometer on the oven door and the clock enable results to be obtained which will be particularly appreciated by the large and growing number of educated and refined women who have to do their own cooking—indeed it may not be an exaggeration to say that the splendid results obtainable may make cooking attractive to many intelligent people.

The cooker installed is of the table type; that is, the oven is alongside the boiling-table. This avoids stooping or kneeling when attending to the oven—the low oven seems to be designed to cause irritation. The oven and the griller can be given unstinted praise.

The boiling-plates—two in number—are rated at 1½ kW and 2 kW respectively and are of the open type. Though satisfactory, when properly maintained, manufacturers must try to do better with their boiling-plates. Safety and speed are the ideals at which to aim. The efficiency of the open-type boiling-plate may be 20 to 25 per cent when starting from cold—or little better than that of a coal fire. Numerous experiments made by the author have shown that substantial improvements are possible—see "cooking" load curve in Fig. 7 showing the fall in consumption—and no one will be better pleased than supply undertakings when makers can improve the efficiency and reduce the upkeep charges of boiling-plates. In this connection it may be noted that investigations are being made with various types of boiling-plates and cooking utensils.

Probably in some households it would be better to provide three boiling-plates on the boiling-table, while a large and a small oven might be an advantage. It has been found that rustless steel makes excellent baking shelves for ovens.

In passing, a thought may be given to the question of development. Are we proceeding along correct lines? Is not an electric range an imitation of a coal or gas range, and are we certain thereby to utilize to the best advantage the unique merits of electricity? Instead of the present inefficient boiling-plates, may it not be better to use a number of economical cooking utensils each with its own heating element, like a kettle, and fitted with watertight plugs? The idea, though old, is at least worth consideration.

(8) Hot Water.*

It has long been recognized that the provision of an abundant supply of hot water in an all-electric house presented a tough problem, owing to the large amount of energy required for this purpose. Here, above all, a low tariff is essential. True, it is possible to use small tanks or geysers in different parts of the house and so avoid all pipe losses; but an adverse critic, or one accustomed to an ample supply of hot water at all times, might regard such methods as a makeshift.

The solution adopted in this case was made possible by Mr. R. B. Mitchell, the City Electrical Engineer at Glasgow. When first discussing the author's proposals for an all-electric house and the effect of domestic load on load factor, Mr. Mitchell produced load curves similar to those shown in Figs. 5 and 6, and emphasized the desirability of developing new forms of night load. No better occasion offers itself for this purpose than heat storage in water. Not only is the load large, but it is constant throughout the year, while it can be taken only during the hours when the supply undertaking is best able to give it. It was therefore decided to take energy for heating water between the hours of 11 p.m. and 7 a.m. As regards a tariff, it is obvious that such energy must be cheap enough to make the proposition feasible. But here, again, the situation proved to be favourable. Since the consumer's share of the capital charges is included in the two-part tariff already referred to, it follows that running charges will form practically the entire cost. The average running charges at Dalmarnock station, in which coal, of course, is the chief item, are of the order of 0·25d. per unit; and the charge of 0·375d. per unit proposed by Mr. Mitchell for current

* S. Parker Smith and N. M. MacElwee: "The Heating of Water by Electricity for Domestic Purposes," *World Power*, 1926, vol. 5, p. 7.

for domestic hot-water storage during night hours therefore appears to be reasonable, and should become popular. In order to make the experiment successful, however, it was necessary to obtain a well-lagged tank. This proved to be a difficult task, but the author was fortunate in obtaining the co-operation of Mr. Duncan Low of Messrs. Arch. Low and Sons of Glasgow.

For several weeks tests were made with different forms of lagging until at last it was found that with a suitable application of cork the fall in temperature of the water was less than 1 degree F. per hour. Further, it

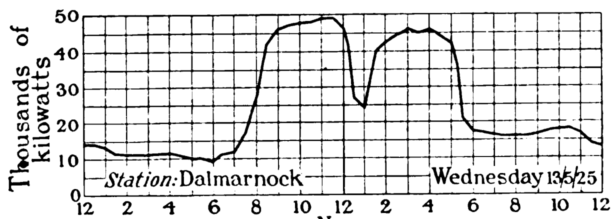

FIG. 5.

was found that by proper design the amount of mixing of the incoming cold water with the hot water in the tank could be made negligible. The tank installed is fed from the cistern and has a cubical capacity of 87 gallons. It supplies the bath and hand-basin in the bathroom, the maid's room, pantry, cloak-room and three points in the kitchen. Near the bottom of the tank there are immersion heaters rated for 4 kW, 2 kW and 1 kW. Near the top of the tank there is an emergency immersion heater rated at 2 kW. This

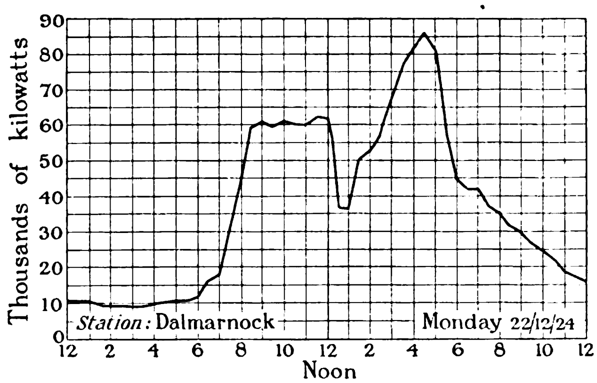

FIG. 6.

auxiliary heater has proved to be very serviceable when the demand for hot water has been exceptional and the temperature has fallen too low for domestic purposes. For instance, it will heat up sufficient water for a 35- to 40-gallon warm bath in 30 to 60 minutes, according to the water temperature when switching on.

The tank is fitted with a thermometer which is calibrated " high," " medium " and " low," to indicate in which position the switch has to be placed in the evening. Experience has shown that in winter it is mostly necessary to place the switch at night in the " medium " position: in summer it is occasionally possible to switch on to " low." As a rule the tank is switched on about 10.30 p.m. and off at 7.30 a.m.—which partly accounts for the " hot-water " load curve being higher than the night load curve in Fig. 7. Under the above conditions, the temperature of the water on switching off is usually in the neighbourhood of 140° F. —it is seldom as low as 120° F. or higher than 160° F. In addition to the house service throughout the day, there is sufficient water for two hot baths per day. The tank is placed in the bathroom, so that any heat loss is useful in warming this room. As a result, the temperature of the bathroom is always comfortable, and it is seldom necessary to close the window or use a fire.

The question may well be asked—why not heat the water to, say, 180° F. and so install a smaller tank? This would certainly be feasible and cheapen the first cost, but there are advantages in having the larger tank and using water between 120° and 140° F. The losses from the tank and the pipes are much less at the lower temperature. Experience shows that it is more economical to supply water to the kitchen at the lower than at the higher temperature. Moreover, the possibility of working at the higher temperature in case of need gives the tank a good overload capacity.

Since the tank was installed no trouble whatsoever has been experienced and there has at all times been an ample supply of hot water—equal to some 12 to 15 gallons per person per day. Without asserting that the above method is the cheapest for obtaining hot water, Table 3 will show that the cost is reasonable. The value of such a night load to the station and the convenience of the method will scarcely be disputed. By means of a thermostat it is a simple matter to arrange automatic heat control for such a tank.

As far as the author knows, this method has been widely adopted only in places served from hydro-electric stations, but it is encouraging to find that supply authorities in this country are beginning to give attention to the matter. For example, the Clyde Valley Power Company are prepared to sell energy at ½d. per unit for domestic water-heating during night hours. It is possible that this charge may be reduced to ⅜d. per unit. The Corporation of Greenock are offering energy for the same service at ½d. per unit to all classes of domestic consumers. Supply authorities might also consider the desirability of hiring out storage tanks to consumers.

(9) VENTILATION.

The scheme of ventilation adopted is simple and effective, and its only drawback is the dirtiness of the ventilating medium—a drawback associated with all houses built in or near large towns. Fresh air is drawn into the rooms through air bricks behind the fires in the recesses, and the amount of air can be regulated in a simple manner. The outlet for the vitiated air is a wooden grid let into the frieze and communicating with the flue in the external chimney breast. This arrangement has proved to be satisfactory, and the rooms do not get stuffy when the windows are closed.

The imperfection in the system is not peculiar to this house. In all houses in or near towns, roads, etc., work is caused on account of the dirty or dusty air which surrounds them. To supply rooms with filtered air would

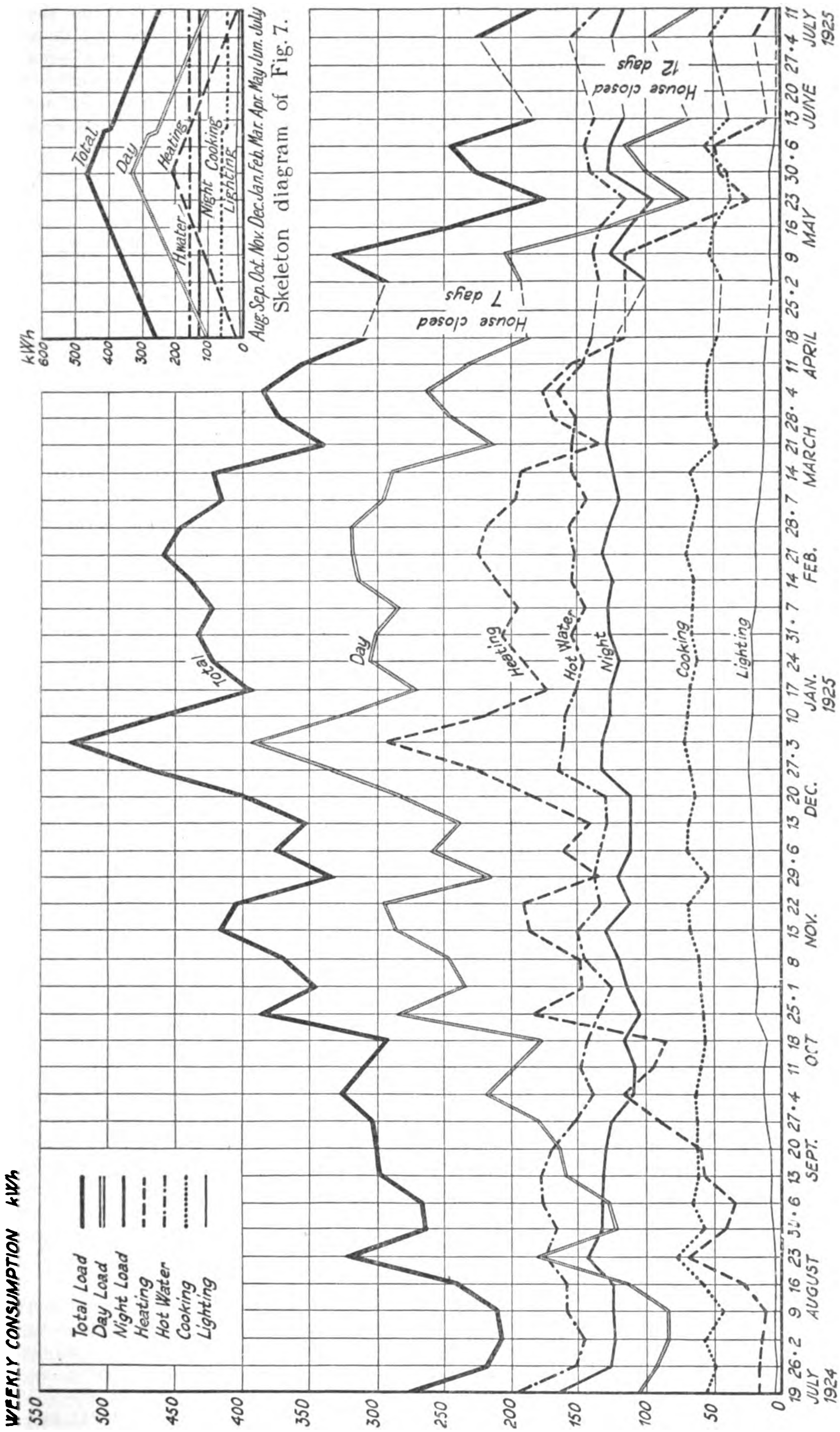

FIG. 7.—Weekly consumption in all-electric 10-roomed house for year 12 July, 1924, to 11 July, 1925.

entail forced ventilation; namely, a small fan, filter and ducts to lead clean air into the several rooms. If this method were adopted the air could, if necessary, be slightly warmed by passing it through a convector before it leaves the outlet channel. Provision has been made for the possibility of forced ventilation (e.g. circuit marked "Bst" in Fig. 4), but the full details have not yet been worked out, as the need has not arisen. It might be necessary to place the fan in the garage to prevent noise in the house.

If country areas were supplied with electricity at reasonable rates and local lines were electrified, this problem might not arise: at present the effects of our backwardness in air purification are keenly felt.

(10) Heating.

The question of heating by means of electricity is a fruitful subject for debate. Doubtless individual predilections have an important bearing on the decision arrived at. Broadly speaking, there are two alternative ways of heating to be considered, convection and radiation. In the former case the air is first warmed by means of air warmers (e.g. hot-water convectors, anthracite stoves, etc.). In the latter case persons are warmed by means of radiant heat (glowing fires—whether coal, gas, or electric).

The author discarded the former method of living in heated air as being inferior to the latter for the home. As is well known, the human body appreciates heat rays whether from the sun or from a glowing fire. Moreover, radiant heat is more pleasant in a cool than in a warm atmosphere, as is often experienced on a sunny day in winter, or in the morning and evening of a summer's day. The value of a coal, gas, or electric fire is determined mainly by the amount of heat radiated, and to a much less extent by the amount of convected heat (warmed air).

The electric fire renders it possible to obtain radiant heat in rooms with cool air, while owing to the portability of such fires the heat can be directed just where it is needed. Naturally, after a time the air becomes heated by the warmed objects in the room, etc., but the room can be kept cool by adequate ventilation. Experience shows that with ample radiant heat an air temperature of 50° to 55° F. is very comfortable; whereas with warmed air, 62° to 65° F. is desirable.

To obtain the best results from electric fires care must be used to have the heat where it is needed. In cold weather it is often much better to have two or three small fires suitably distributed in a room than even one large fire.

The fires for occasional heating—as in bedrooms, etc.—should be portable and, when in use, placed where they are needed, e.g. near the dressing-table, bed, etc.

As regards comfort, it has only to be mentioned that no difficulty or inconvenience of any kind has been experienced. The coal fire is not missed, while the ease with which the heat can be distributed and controlled is an advantage that would not be readily sacrificed when once enjoyed. The large number of attractive designs available render it possible to choose a fire that will harmonize with any style of decoration.

It is possible, of course, to make use of heat-storage stoves which can be switched on during the night hours. In the author's opinion, however, the disadvantages of such Dutch stoves—great bulk, weight and cost, and heating by convection—act decisively against them. Moreover, the radiator load in the home, though large, reaches its maximum in the evening, and thus occurs after the afternoon peaks during the winter; consequently the domestic heating load is not troublesome to the power station.

(11) Running Costs.

There are many features in an all-electric house, the value of which it is hard to appraise. Thus, saving in domestic labour, cleanliness, health, freedom from smoke or fumes, etc., may all have an actual money value, but on what is this value to be reckoned?

Then, again, what may be called the higher standard of living rendered possible by the many additional and genuine comforts and conveniences of electrical appliances has a real value. Nor would it be correct to put these down as mere luxuries—they become necessities in the same way as a water service.

Ignoring, however, for the sake of argument all these advantages, it is valuable to study the actual running costs of an all-electric house.

The figures in Tables 1, 2 and 3 set forth the consumption and costs for the above 10-roomed house for one complete year. It will be seen that heating, cooking, hot water and lighting have been separately metered. The small discrepancies between Tables 1 and 3 are to be accounted for by meter inaccuracies. The analysis in Table 3 is based on a total day consumption cost of £33 19s. 2d. divided in proportion to the day meter readings in Table 2. The curves in Fig. 7 represent the weekly consumptions of these items.

In order to compare the costs for a smaller all-electric house, the figures obtained by Mr. B. Hague for a four-roomed flat are given in an Appendix. Mr. Hague's charges are based on the same two-part tariff as the author's.

(12) Conclusions.

Costs.—The figures in the tables are of interest both to the supply engineer and to the consumer. For the consumer, the first question will probably be that of relative costs, apart from merits and demerits. Now, a true and fair comparison can scarcely be made unless corresponding costs are available for similar services obtained from coal, gas and electricity in some combination or other. Unfortunately, not many householders keep sufficient data to check their annual expenditure on coal, coke, anthracite, gas, oil, candles, firewood, matches, etc. A fair estimate can, however, be made when some of the smaller items are omitted, though there are doubtless many cases where it would be irksome to keep accurate accounts, e.g. where coal is purchased in small quantities. Nevertheless, such information is needful wherever fair comparisons are to be made. In the author's case, the all-electric house in Glasgow cost practically the same as a somewhat smaller house in Wimbledon in which coal, gas and electricity together cost £42 and £45 in two successive years. Here, however, much less hot water was obtained.

TABLE 1.

All-electric House (10 *Rooms*).

Energy costs for 52 weeks (4 quarters). 12th July, 1924–11th July, 1925.
Six persons in house, excluding guests.

		£	s.	d.
Main 2-rate meter:				
	Fixed charge	12	10	0
Day load.	10 299 units at 0·5d. ..	21	9	2
Night load.	6 043 units at 0·375d. ..	9	8	10
	Total cost for year ..	£43	8	0
	Average cost per week		16	8
	Average cost per day		2	4½
	Average cost per day per person ..			4¾
	•Average cost per unit—*day consumption*			0·791d.
	Average cost per unit—*total consumption*			0·637d.

TABLE 2.

Analysis of Consumption in Units.

Separate meters	Total	Average		
		Weekly	Daily	Per day per person
	units	units	units	units
Heating ..	5 954	114	16	2·74
Hot water ..	1 242 day 6 043 night	140	20	3·33
Cooking ..	2 777	53	7·5	1·27
Lighting ..	568	11	1·5	0·26
Total ..	16 584	318	45	7·60

TABLE 3.

Analysis of Costs.

Separate meters	Total	Average		
		Weekly	Daily	Per day per person
	£ s. d.	s. d.	s. d.	d.
Heating	19 3 7½	7 4½	1 0½	2
Hot water	4 0 0 (day) 9 8 10 (night)	5 2	9	1½
Cooking	8 18 11½	3 5	6	1
Lighting	1 16 7	8½	1	¼
Total ..	43 8 0	16 8	2 4½	4¾

In a slightly larger house in Helensburgh, using coal and gas, the costs were somewhat higher—varying from £58 to £44.

As a comparison with Mr. Hague's figure in the Appendix, it may be mentioned that a Glasgow bungalow with three persons using coal, gas and electricity cost £15 15s. per annum. In these cases the smaller items, such as firewood and matches, have been ignored.

Roughly speaking, the author would say that with energy at about one penny per unit and a low tariff for

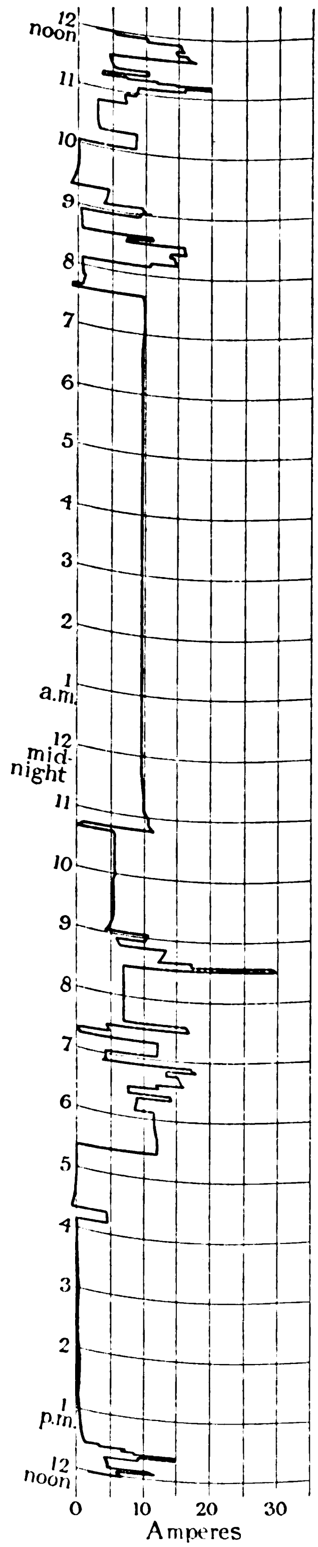

FIG. 8.—Load curve for Monday, 25th August, 1924.

Average height = 6·74 amps.

water heating there would seem to be very little difference between the cost of an all-electric house and the same house using coal, gas and electricity. Consequently, on the score of running cost, even when the manifold advantages of electricity are entirely ignored, the objection to the all-electric house herein described cannot be sustained.

The author would suggest that interested consumers should collect data to enable comparisons to be made with the figures in the tables.

Load factor.—The supply engineer fortunately can see at a glance how valuable is the load of an all-electric house. The hot-water and cooking loads are practically constant throughout the year and together form some 60 per cent of the total energy consumption. Moreover, a part of the constant load representing 36 per cent of the total load is taken at night-time. It is also interesting to see how unimportant lighting becomes both as a load and as a source of revenue when all services are worked electrically. Thus the all-electric house in question has an aggregate consumption of about 30 times the lighting consumption, and this practically without increase of station plant. An example of the daily load curve is shown in Fig. 8. This was taken by the Glasgow Corporation Electricity Department and represents the demand on a day when room-heating was practically restricted to the evening hours.

Reliability.—As regards reliability, it need only be said that as yet the service has not once failed.

Maintenance.—Upkeep should not be a serious item when cookers and fires can be hired and are kept in order by the supply undertaking. Actually, however, very few repairs or renewals are needful. Minor faults causing varying degrees of annoyance occur in electrical appliances, owing to faulty design or inspection in manufacture. Probably the weakest part of the installation is the flexible cord between the plug and the appliance. Makers might take note of these points.

Refuse disposal.—Careful observation has shown that by using a small, closed refuse-bin no nuisance of any kind whatsoever has resulted—the bin is emptied twice weekly, and refuse has never been less troublesome to the author than at present. It is difficult to see how garbage disposal can seriously affect the question, or even entail the use of an incinerator on the premises.

Boiler coal versus house coal.—An interesting point arises in connection with coal consumption. Dalmarnock generating station uses about 1·8 lb. of coal per unit generated. Assuming then, for the sake of argument, that a unit delivered at the house needs 2·24 lb. of coal, then 1 000 units require one ton. Consequently, between 16 and 17 tons of coal would be needed at Dalmarnock annually to supply the services of the above all-electric house. This amount of house coal—assuming that all services could be obtained from raw coal on the premises—would cost, let us say, £33, while the coal used at the station would cost less than half this amount. For the coal industry it is probably better to increase the demand for station coal rather than for house coal; while as regards convenience, etc., the householder will readily forgo the handling. That this mode of working a house entails a relatively large amount of coal is, apart from enhanced conveniences, essentially due to the inefficient method adopted for obtaining electrical energy.

Cooking.—The drop in cooking consumption seen in Fig. 7 is mainly due to lighter grids, raised elements, and blackening the bottoms of utensils. Increased efficiency means reduced cost—an important matter in the development of electric cooking. At the same time, indestructible elements are no less important. Speed and indestructibility are the ideals to aim at in the design of boiling-plates. The merits of separate utensils with built-in elements are receiving closer study.

Development.—Though domestic apparatus has now reached the stage when reliability can be guaranteed, much remains to be done. Manufacturers should aim at improving designs, avoiding inferior workmanship and careless assembly, and, above all, reducing the cost of domestic appliances. Backward supply undertakings throughout the country should mend their ways by reducing their charges for the domestic load and hiring out appliances on a commercial basis. Electrical contractors should encourage consumers as energetically to install appliances as to adopt electric lighting, and ensure that all wiring work is carried out in a conscientious and sound manner. Technical men should undertake researches relating to household appliances.

Advantages of an all-electric house.—The manifold advantages of the all-electric house will probably appeal chiefly to people whose habits are not inflexible and to innumerable small households where coal merely means drudgery. As regards cost, with electrical energy not exceeding 1d. or even 1½d. per unit overall, it would seem to be feasible, particularly where no maid is kept, to work large, medium or small houses electrically, though the cost of installation may remain a difficulty. Fortunately, this matter seems now to be receiving the sympathetic attention of supply undertakings, and it may therefore be not too presumptuous to look forward to a time in the near future when the full advantages of electricity in the home will be available to all. Among the advantages associated with electricity, cleanliness and health may well be emphasized. The absence of coal fires in a house like the one here described may make it possible to dispense with one domestic servant and thereby not only more than repay the total cost of the electrical energy, but also lighten the domestic labour problem. Equally, the improved health of the household and of the community, by eliminating smoke, is an inestimable benefit. Again, the rational mode of distributing and controlling heat is a great boon, Internal decorations seldom need renewal: cut flowers may last a month or even longer. Numerous minor luxuries become normal comforts and conveniences.

APPENDIX.

Results of an All-electric Flat.

(*Communicated by Mr. B. Hague, M.Sc., Associate Member.*)

The particulars and figures given in this Appendix refer to the past year's electric working of a tenement flat with three rooms and a kitchen in

the west end of Glasgow. These may be of interest since they demonstrate the possibility of utilizing the "all-electric" principle in a quite different type of dwelling from that described in the paper. Tenement flats are so common in Glasgow and the domestic smoke nuisance is so acute that the application of electric operation at economical rates to such property is a matter of considerable social importance.

The flat is situated at the top of the building, so that the bringing up of coal and the removal of ash present real problems. The household consisted of two persons and was run without a maid, but with the aid of occasional labour. In order to reduce to the absolute minimum all causes of domestic drudgery, it was decided to install electric appliances for lighting, heating, cooking, hot water, and auxiliary services.

One of the regular criticisms levelled at the abolition of the coal fire and the adoption of electric heating is

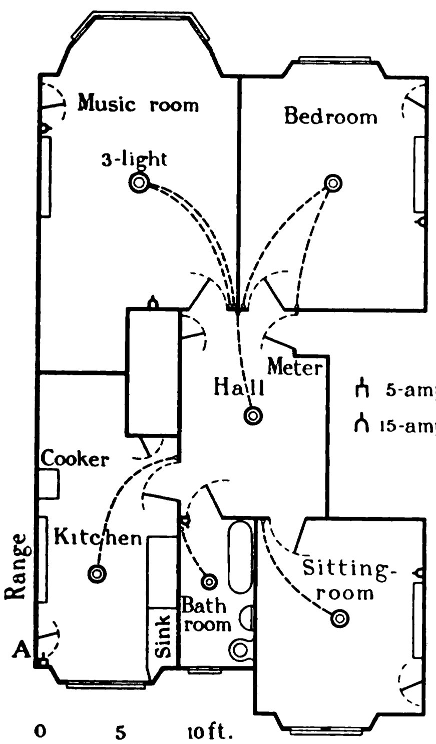

FIG. 9.—Plan of all-electric four-roomed flat.

that there is no place in which to incinerate household refuse. A little forethought and care have, however, overcome any difficulty in this connection.

Wiring.—The building in which the flat was situated is about 15 years old, and had not previously been wired for electric supply, and thus represents a case of conversion. Advantage was taken of the scheme of the Glasgow Corporation Electricity Department for the wiring of old property on the following basis: (1) The landlord bears the cost of installing the rising main from the street to all floors of the building. (2) The tenant pays for the installation in the particular flat occupied by him.

The charges are exceedingly moderate; in the case of the present installation £10 was charged for the wiring. Since the provisions of the scheme were inadequate for all-electric working, additional points and circuits were added to suit requirements; these were charged for as extras.

Fig. 9 shows a plan of the flat with the various circuits. The wiring is of lead-covered bonded cable throughout, the conductor being 7/·052 copper. The allocation of the circuits is as follows:—

Room	Supplied under scheme	Additional
Hall	Light pendant and switch	——
Bedroom ..	Single light and switch	Two-way switches for light. 15-amp. socket for fire
Music-room	3-light pendant with two switches. 15-amp. socket for fire	15-amp. socket for fire
Kitchen ..	Light pendant with switch. 5-amp. socket for iron	Wiring for cooker and immersion heater
Bathroom..	Light pendant and switch	15-amp. socket for fire
Sitting-room	Light pendant and switch	15-amp. socket for fire

Sockets throughout are B.E.S.A. Standard and, with the exception of the 5-amp. socket for the iron, are not provided with switches.

Supply.—Current is taken from the 250-volt d.c. supply of the Corporation Electricity Department. Since the economical use of electricity in houses depends so entirely on the fixing of a rate of charge sufficiently low to attract the domestic consumer, the question of tariffs may here again be considered. The choice of the correct rate is a matter determined by the annual demands of the consumer. The two schemes are as follows:—

(*a*) *Ordinary tariff.*—In this system, by which a certain number of units M are charged at $4\frac{1}{2}$d. per unit, and any excess number of units at $\frac{3}{4}$d. per unit, the cost for an annual consumption of X units will be $4{\cdot}5M + 0{\cdot}75\ (X - M)$ pence. For the flat in question M is fixed at 120 units, making

Annual cost in pence $= 450 + 0{\cdot}75X$, or

$$\text{Annual cost in £} = 1{\cdot}875 + \frac{X}{320} \quad . \quad . \quad (1)$$

The cost per unit in pence under this scheme will be:—

$$\left.\begin{aligned}\text{Cost per unit} &= \frac{450}{X} + 0{\cdot}75, \text{ when } X > 120 \text{ units}\\ &= 4\tfrac{1}{2}, \text{ when } X \lessgtr 120 \text{ units}\end{aligned}\right\} (2)$$

(*b*) *Two-part tariff.*—Under this system, a capital sum $£F$ is charged, approximately one-eighth of the annual rateable value, plus the cost of the entire consumption reckoned at $\frac{1}{2}$d. per unit. In the present house $F = £5{\cdot}2$, so that—

Annual cost, in pence = 1 248 + 0·5X, or

$$\text{Annual cost, in £} = 5{\cdot}2 + \frac{X}{480} \quad . \quad . \quad . \quad (3)$$

and

$$\text{Cost per unit, in pence} = \frac{1\,248}{X} + 0{\cdot}5. \quad (4)$$

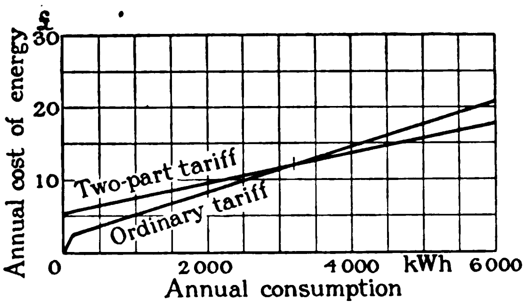

FIG. 10 (*a*).—Annual cost of energy at Glasgow rates.

Ordinary tariff:—4½d. per unit for 120 units and ¾d. per unit thereafter.
Two-part tariff:—Fixed charge of £5 4s. All energy at ½d. per unit.

In the present instance, the two methods of charging give identical annual costs for a consumption of 3 192 units. Fig. 10 (*a*) shows the graphs of Equations (1) and (3), from which it is seen that for a large domestic supply the two-part tariff is the cheaper of the two methods. This was accordingly adopted. Fig. 10 (*b*) shows the cost per unit in the two schemes, from Equations (2) and (4).

The following apparatus has been installed :—

Cooking.—Cooking is done on a 7-kW cooker hired from the Corporation at a charge of £1 for the first year and 10s. for subsequent years. The cooker is maintained in working order by the Corporation and is wired gratis. This appliance is of the customary type with a 2-kW oven surmounted by two boiling-plates, one of 2-kW and one of 1·5-kW loading, and a 1·5-kW griller. The oven and boiling-plates are provided with 3-heat switches.

The cooker has proved in every way satisfactory: the oven and griller are excellent; the boiling-plates, a little slow, are also satisfactory. It was found that

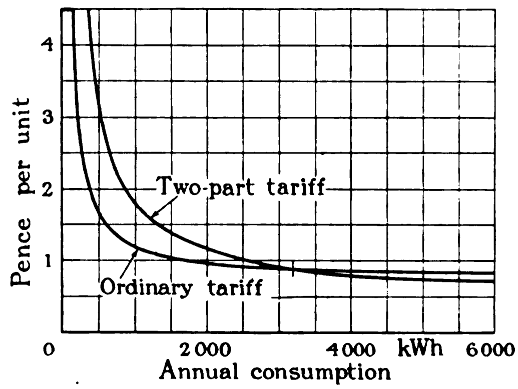

FIG. 10 (*b*).—Cost per unit at Glasgow rates.

there was no operation of cooking previously done on a gas cooker that could not be done equally well on the electric cooker, though sometimes a slight modification in culinary technique was necessary to enable the maximum of success to be attained. The certainty of results to be obtained by the use of the cooker has proved an invaluable asset to the housewife.

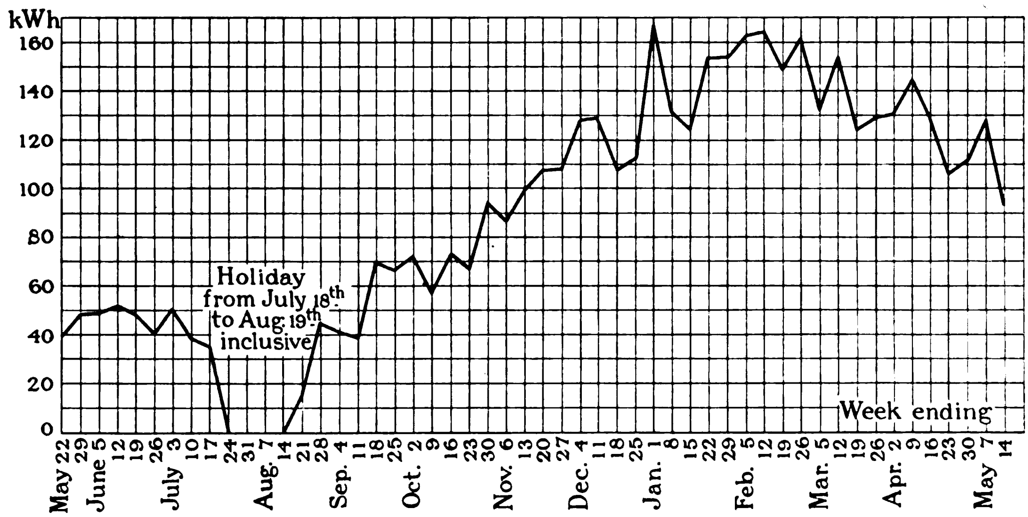

FIG. 11.—Weekly consumption in all-electric four-roomed flat, 22nd May, 1924, to 14th May, 1925.

Hot water.—Hot water for ordinary domestic purposes, cooking, washing-up, etc., has been satisfactorily supplied by a 3-pint kettle rated at 825 watts and hired with the cooker. This has been supplemented by a 2-pint, 575-watt kettle for additional purposes.

The provision of hot water on a larger scale for baths, and for such washing as is done at home, extra cleaning, etc., is made by the installation of a "High-low" 1–2–3-kW immersion heater. This heater is fitted in the hot-water tank of the household hot-water system, necessitating no more than the cutting of a

hole in the tank and the fitting of the flange for the reception of the element. The tank is situated above the cupboard in the kitchen at the place marked A in Fig. 9; the service pipes pass overhead directly to the sink and bathroom. The tank was specially lagged with a thick layer of hair felt; this and the shortness of the pipe-line make the thermal losses extremely low.

The heater has proved very satisfactory. The tank contains 22 gallons of water, which can be brought to a temperature of about 110° F. by the application of 3 kW for 1¼ to 1½ hour, according to the temperature of the cold feed.

Heating.—When the flat was first occupied, heating was done by one 2-kW and one 3-kW fire hired from the Corporation at 8s. and 12s. per annum respectively. A little experience, however, soon showed that it is best to use not one large heating unit but several small ones distributed about the room, and the 3-kW fire was therefore, later on, replaced by two 2-kW units. It has been found that the most satisfactory way of heating is to apply for a short time, say ½ hour, a high power, and then to reduce the power to the required amount. It is found that satisfactory ventilation can be obtained from the now unused fireplaces, combined with the judicious use of opened windows. It should be noted that the fires are *not* placed in the fire recesses, but are set out in the room where most required. For heating in bathroom, etc., a 750-watt bowl fire is used.

Results.—In presenting these results of a year's working, it is essential first to realize what the costs represent. They provided for a household of two persons (not counting guests and occasional labour), lighting, cooking of meals, hot water for domestic services and baths, heating of rooms (inclusive of occasional heating of bathroom and bedroom) and small auxiliary services. Only a single meter was provided, and this was read daily. No attempt has been made to allocate the consumption among the various items, but an analysis of the daily readings serves to verify the general conclusions given in the paper, viz.:—(1) Lighting is a small factor; (2) cooking is a fairly steady load; (3) heating is the cause of the greatest consumption and fluctuates greatly in response to seasonal variations of temperature.

The variation of weekly consumption throughout the year is shown in Fig. 11, and the energy costs are given in Table 4.

Conclusion.—It will be observed that the cost is reasonable, especially when it is remembered that no further charges for gas, coal, or any other heating or lighting material are involved. Beyond ordinary care to avoid waste, such as would be undertaken by any reasonably economical householder, no special care has been exercised.

One figure, often quoted in statistics of this nature, requires comment, namely the cost of energy per person per day. This figure in itself is a misleading criterion of the working of any scheme unless it is accompanied by a statement to show what services are rendered for the price. If the present household were increased to 3, in none of the services would the consumption increase in proportion to the larger number of persons. Hence the cost per head per day would fall roughly to perhaps three-quarters of the preceding figure for the same domestic facilities. Thus it will be seen that the cost per day is a truer criterion than the cost per day per person. This is also borne out by comparison between Tables 1 and 4, which show the cost per day per person to be practically the same, whereas the services in the larger house were greater than in the smaller house.

Finally, it remains to be mentioned that the supply was maintained by the Corporation with perfect continuity throughout the year. Maintenance has only been a slight item. In the year two boiling elements have been replaced in the cooker, and one lamp has burnt out—speaking well for the reliability of the apparatus installed.

TABLE 4.

All-electric Flat (4 Rooms).

Energy Costs for year ended 14th May, 1925.

Total consumption for year, 4 656 units.

Cost of energy at ⅛d. per unit			2 328d.
Fixed charge of £5·2			1 248d.
			3 576d.
	£	s.	d.
Total cost of energy	14	18	0
Average cost per week		5	9
Average cost per day			10
Average cost per day per person			5
Average cost of energy per unit			0·768d.

The cost of hiring the cooker and two fires was £2.

DISCUSSION BEFORE THE INSTITUTION, 3 DECEMBER, 1925.

Colonel R. E. Crompton: During the last 30 years of the period which has elapsed since we began to use electricity for lighting purposes, at first in detached installations and in or about 1889 by putting down central stations for supply, I have had before me the immense advantages of trying to persuade users to adopt electricity for heating, cooking and as a domestic source of power, so as to raise the load factor of a purely residential district from that due to lighting—which used to be as low as 10—to a hoped-for figure of 25. We in London have already taken a substantial step forward; the load factor has, even in the purely residential districts, already risen, due to its use for heating and cooking, to about 20 or thereabouts, and this has had a material effect in reducing the average price to the public. I therefore welcome the paper as a practical addition to our knowledge of what can be done, if and when electricity can be supplied as cheaply as has apparently been the case in Glasgow. I think that the Glasgow Corporation were quite right in quoting the author specially low prices, but I am afraid that in London at any rate there is little chance of reaching

such figures. It is fortunate that the author was able to show considerable designing power as an engineer, and he is to be congratulated on the excellent results which he has obtained. He refers to the undoubted fact that in the past there has been far too much imitation; the gas fire has imitated the coal fire, and the electric fire has imitated the gas fire, and even the author has, as the lantern slides show, been impressed by the tradition that he must show a fireplace as a means of heating a room by radiation. I personally have for many years been trying to find out how electricity can be used to the best advantage for heating, in order that I might have reasonable arguments to put before our customers to induce them to adopt electrical heating and cooking. A very strong case can be made out for heating by radiation from electric radiators placed close to the person who has to be warmed. A very small radiator placed near a person working in an office will enable him to work in comfort in a room otherwise far too cold for his health or comfort. In the bedroom this is even more the case. Although I am an old man and require artificial heat much more than younger persons do, I found that in the recent cold snap when the air of my bedroom was at 40° F. or thereabouts I could obtain absolute comfort by a radiator which was placed conveniently near to my bedside and could be moved close to the dressing-table when I got up to dress. As this radiator is only on for very few half-hours the cost, even at the London price of 1¼d. per unit, is ridiculously low and is actually far less than the cost of warming the same bedroom by central heating or by a gas fire. But at the present time we *must* take advantage of the convenience and portability of our radiating units. In London we should be able to show little or no advantage if we retained the traditional fireplace, but with a portable heater the case is very different. In the case of electric cooking we can show great advantages over gas cookers; all roasting and similar processes done in the oven by gas are carried out by radiation from gas flames, the oven must therefore be thoroughly ventilated and a calorific loss follows thereon, whereas with an electric oven there need be no ventilation, and the flavour of the meat is retained so that meat and game cooked electrically are distinctly superior, as regards flavour and economy of the meat juices, to anything possible in the best-designed gas cookers. The author has put very valuable facts and data before us, which will be of great use to all who are trying to forward the cause of electric heating and cooking.

Dr. S. Z. de Ferranti: The outstanding feature of the paper is the faith which the author has had. Faith in this case has enabled him to produce an installation which is of very great value. It has also enabled him to equip his home in such a way that he will live with a much greater degree of material comfort than he could possibly have done if he had not carried out the work so thoroughly. My experience is that the greatest disadvantage of an all-electric house is that there is nowhere to throw those odds and ends that would ordinarily be thrown on the fire. In my case we have had to install a refuse destructor at some distance from the house. To come to a most important feature, the author has explained the desirability of heating by radiation. Heating plays a very big part in any system of satisfactory house equipment, and it is all-essential to heat by radiation; every process which heats up the air in a room is unsatisfactory. What we want to do is to live in a comparatively cold atmosphere and to be kept warm by radiant heat. In Switzerland one lives all day out in the open in winter time in an atmosphere many degrees below freezing point, and yet one is perfectly warm so long as one keeps in the sun. Living in hot air has an enervating effect, and I understand from doctors that the lungs require a fair amount of comparatively cold air to keep them in good condition. Electricity gives us radiant heat in the best form. As may be gathered from the paper, the heating in the author's house is provided by radiant electric fires which do not appreciably heat the atmosphere but which heat the occupants of the rooms. The author says that it is not his business whether the Glasgow Corporation makes a profit or not, but I think it is a matter of national importance. Nothing should be run at a loss. My opinion is that there is no question that the Glasgow Corporation is making a profit on this business. The chief engineer is a business man and knows perfectly well what he is doing in encouraging the author to make his home an all-electric house. Unfortunately, electricity is very dear in many places. There are various reasons for this, the principal being the small extent of the business. Again, there is the poor load factor—i.e. the short hours during which the capital is utilized—and, especially in London, the excessive rating of supply undertakings. All these difficulties could be very largely overcome if electricity were used for the whole of the 24 hours. That is the commercial solution: let better advantage be taken of the present capital. Our great handicap in electrical work is that we have no efficient means of storing electricity. Batteries store it perfectly well by chemical action, but the capital cost is heavy and the maintenance cost is also heavy, and it would not pay, I think, for every house to have a battery to take electricity for the whole 24 hours and to use it at the times that it is required. Fortunately, however, a large amount of the heat we require in a house is low-grade heat, and that we can store in the form of hot water. Hot water is a very cheap form of energy storage and, as pointed out in the paper, the provision of a large water tank enables electricity to be taken at a time when it has practically no value—when the capital invested is practically lying dead—and turned to good account by storing energy in the form of hot water which is used at any time during the rest of the 24 hours. I think that further development along these lines will do much in the way of solving our electrical difficulties. The particular house described in the paper cost £43 a year for current, and at that rate, as I have said before, I think it pays the Glasgow Corporation very well. This £43, in my opinion, is not nearly the value of the service which the author gets from the supply. If he were to try to run his house without electricity, by other means, he would not spend much—if anything—less on the direct services that he has described, but all sorts of other expenses would be involved which, I think, would mount up to several

times what his electricity bill comes to to-day. I should like to add a few words with regard to my own experience of an electric house. I live 13 miles from the nearest source of supply, Sheffield, and some years ago I put an electric installation into the house. This installation has been modified from time to time, and is at present not complete, although now, and in fact for the past 6 months, we have had no fires in or near the house for any purpose. We burn no coal or coke, and use no gas. We burn crude oil in a 25 h.p. engine. Our maximum load up to the present has been 18 kW. This is at a time when the battery is assisting the engine. The whole or a very large portion of the heat of the jacket water and of the exhaust is used to supply the hot-water storage in the house. In a case of this kind probably about 25 per cent of the fuel energy is obtained in the form of electricity, and the jacket water and the exhaust would probably add another 50 per cent. I have a storage battery containing, I think, about 2 tons of lead, and the hot-water storage is a tank in the basement 6 ft. in diameter and 6 ft. 6 in. long, with about 6 in. of insulation. This tank holds about 6 tons of hot water. We therefore store our energy in about 2 tons of lead—the electrical part—and 6 tons of water—the low-grade heat storage. The capital cost of hot-water storage is of course much less than that of direct electrical storage. We find that with this particular plant we get all the hot water that we require for baths and washing and house-heating. The system of heating the house is in accordance with what I have already said on that subject, i.e. it is true heating by radiation. All the principal rooms have invisible panels in the ceiling, consisting of pipes bedded in the plaster below the surface. The general heating is therefore taken care of by radiation at low temperature from the ceilings of all the principal rooms, and not by heating the air by convectors, which are wrongly called radiators. The reason for placing the panels in the ceiling is that they shall not heat up the air; the idea is to have in the top of every room a layer of stagnant hot air which keeps the surface of the ceiling reasonably warm, i.e. which does not take away by convection from the heat in the ceilings. The heating is produced by radiation at low temperature from the warm surfaces. The temperature at the surface of the ceiling, where one wants the heating, is 110°–120° F. The high-grade radiant heat is produced by electric radiators. Every room has one or more electric radiators of various kinds in it. The heat efficiency of the whole installation is extremely high; I think that something over 75 per cent of the heat in the oil is usefully employed in one form or another in the house from the high-temperature form of light to the low-temperature form of low-grade heat radiation. It is interesting also because of its bearing on the true all-electric house such as that described in the paper. I feel that by one process or another we must find means to enable the population of the country to do all its work electrically. The advantages of a clear atmosphere are enormous. At present we have done everything we can to shut the sun out from our lives, and notwithstanding our electrical developments we are still making much more smoke than is justified.

Miss C. Haslett: It seems to me that now the electrical engineer has done so much in bringing domestic electricity to its present stage the time has arrived when it is impossible to go very much further without taking into consideration the woman's point of view. I think also that one must not regard electricity supply simply as a trade or a profession, but as a great social service. As the author has said, it is part of the duty of the electrical engineer to see that the community benefits to the greatest possible extent from this tremendous force which we have at our disposal. In any case, I think that electricity will be used more and more, if only on account of the fact that the days of a cheap supply of domestic labour are gone. In the past we could get almost all our domestic work done extremely cheaply, but now we have to face the fact that human energy must be replaced in the home by some form of mechanical energy. Another factor which I think will materially alter the whole idea of home life so far as work is concerned is that women are being trained to run their homes much more efficiently than they were in the past. Women will no longer be content with inefficient methods and long, arduous duties. Another reason why electricity will be used more and more in the home is that people are becoming more and more impatient of the prevailing smoke nuisance. I think, however, that certain facts will have to be faced before a general use of domestic electricity is established to any large extent. The public at the moment—and especially the women—believe that electricity is very expensive. That, of course, is still true in a good many places, but women must be led to understand that although electricity does seem expensive they will reap the results in increased comfort, in better health, in greater leisure and in many other ways. Women in general also have an idea that electricity is rather difficult to manage. Unless that belief is got rid of it will be impossible to make much progress; a campaign of educational work is required to tell the public how simple and easy it is to use electricity in the home. I do not think that the author has sufficiently stressed the fact that in order that electricity may become the friend of the community a much greater maintenance service is needed than has as yet been contemplated. Not only must any fault be promptly remedied, but an inspection of the apparatus in the home should be made by someone who will take a great interest in the whole installation so that the woman will feel she has a confidant to whom she can look for advice. I do not think the problem of refuse disposal presents a really serious obstacle. It seems to me that we have become used to throwing things into the fire, and it is rather a bad habit. It is more a custom that we have to get over than a real difficulty. In my own small electric flat I have no fire at all, but I do not find any difficulty in getting rid of my refuse. The author mentioned cooking utensils with built-in elements as a thing which might develop in future. The system has certainly many advantages, but I fear that it will tend to increase the number of utensils which a woman has to buy and accommodate. In these days of small flats the best use possible must be made of all the available space, and for that reason, and also from the point of view of cost, I do not think there is a great deal in that idea. With

regard to appliances, whilst women are very grateful to the engineer for what he has done up to the present, I think that there is room for much improvement. On that question also I think that the woman's point of view will have to be studied. She is the person who uses this apparatus, and is thus in a position to find out a number of things which could be improved. A good deal has been said as to the high cost of electricity in London, but Marylebone, at any rate, is to be congratulated on its enterprise. After paying a very small yearly sum down—I am on what is called the "telephone" system—I get all my current at ⅜d. per unit, including lighting.

Prof. A. H. Barker: The particulars of this all-electric house are of great interest, but the author does not give all those which one might have wished, such as the position and sizes of the windows, the thicknesses of the walls, the experimentally determined heat-loss coefficient of the various rooms, the internal temperatures maintained, the habits of the occupants and so forth, on which the total consumption necessarily depends. I have deduced by calculations from the small-scale figures and particulars given as many of these details as possible. It is not quite clear whether this paper is intended to advocate the general use of the all-electric house. There are in it indications that other persons interested in the electrical industry have advised the author against the proposal as being uneconomical. The impression is conveyed that the author believes the all-electric idea to be generally feasible and in this case economical. If that is his view I do not agree with him at all. I have frequently expressed the opinion that if electricity could be supplied for such purposes as heating and other domestic duties at a really cheap rate, and if the manufacturers would rise to the level of their opportunities, there is no other form of heat either for house-warming, cooking or perhaps even hot-water supply which could compete with it. But, as things are, I believe that the use of electricity for all purposes in a house is in the overwhelming majority of cases an economic impossibility, except where running cost is of practically no account. The figures given here do not seem at first sight to bear out that opinion. Any figures of cost given with reference to any particularly low rate per unit or house or family must of necessity be somewhat misleading. It would certainly be most misleading to give the public the impression that they could run a 10-roomed house on electricity only for something like £40 or £50 a year. Advocacy of an all-coal house, all-gas house, or especially an all-electric house, appears to me to savour, I will not say of fanaticism, but at any rate of unrestrained enthusiasm. There are some things for which gas or solid fuel is obviously more suited than electricity—there are others for which the superiority of electricity is equally unquestionable. Why do not the electric people and the gas people get together and attack this problem in conjunction without prejudice against one another? I should like to discuss the question very briefly from the point of view of the destruction of fuel at the power station. The most efficient fuel-burning super-power station in the world is, I believe, the new Manchester station. It has a gross thermal efficiency of less than 20 per cent; in other words the electrical energy generated is only one-fifth of the energy of the coal from which it is produced. Now, even assuming that the efficiency of every electrical device in the house could be made 100 per cent—of course the actual efficiency does not nearly approach this—the general efficiency of an electric house is therefore limited to a possible 20 per cent, based on the coal consumed. The actual efficiency in any concrete case is lower than this, being in fact the product of the two efficiencies of production of energy and that of its use. Almost any form of reasonably efficient coal-burning domestic appliance has a higher efficiency than 20 per cent. For central heating and hot-water supply it is at least 50 per cent. The gas industry can put 80 per cent of the energy in the coal into the mains. The general efficiency of most gas-heating devices is rarely below 50 per cent, so that as far as fuel alone is concerned the gas industry uses half the coal which is consumed in doing the same work electrically. The fact is that until the thermal efficiency of electric stations can be made much higher than 20 per cent the general use of electricity for all purposes is and must remain uneconomic. It further appears impossible that if cost alone is considered an all-electric house can in practice generally be a really economical proposition, even at ½d. per unit, because there are other methods of heating (such as gas) which are almost as convenient as electricity and generally much cheaper but which have certain disadvantages which electricity has not. For instance, compare the cost of hot-water supply at 11d. per therm with electricity at 2d. per unit and coke at 35s. per ton, which are the prices I am now paying in Beckenham. The calculated cost of heating the author's 87-gallon tank from 60° F. to 160° F., i.e. 87 000 B.Th.U., would be roughly as follows, excluding heat losses:—With electricity at 2d.—52d.; with electricity at ½d.—13d.; with gas at 11d. per therm—13d.; and with coke at 35s. per ton—3½d. I know of no disadvantages of gas supply which would justify anybody in paying four times as much for electricity, neither do I think that the disadvantages of coke-heated supply are such as to justify any economically minded person in paying four times as much for electricity or gas as for coke. Further, with either gas or coke one could heat up such a tank in an hour, whilst with electricity the time would be more nearly 10 hours, so that the electrical heat losses would be 10 times as great. Then, again, is there anybody who has lived in a house reasonably warmed but not overheated (as many houses are) by well-designed hot-water apparatus who would for one moment compare the comfort of such a building with that of one heated by a few electric radiators switched on and off as required? If this 16 000 cub. ft. house of the author's had been heated in this way by electrical energy throughout a normal winter season he would have used not 5 954 but 26 500 units, which would have cost him £55, even at ½d. per unit. Coke to do the same duty would have cost £12, which is exactly what my house costs me, and my house is a good deal larger. I deprecate the publication of figures of cost based on any particular rate, especially such a rate as the ⅜d. or ½d. per unit. One can make the figures just what one likes by assuming

particular rates, and there are very few districts where one can get anything like such a rate. My view of all these matters is that any figures of consumption should only be given in the form not of money cost but of total B.Th.U., per annum and per person, expended in producing the various services. We can then calculate the total cost corresponding to any particular rate per unit and any particular efficiency of plant. The total consumption of electrical or any other energy is obviously a function of the size of the house, the degree to which the house is heated, the efficiency and arrangement of the various parts of the plant, the number of persons, their domestic habits and a multitude of other things. The total cost is obviously proportional to the total consumption and to the rate per unit. The variation between two different families occupying in succession the same house or of the same family occupying two different houses in different districts would be very great. It is not too much to say that the same house occupied in a different way may vary 500 per cent in respect of the amount of heat required for warming it. Similar variations exist for cooking. The hot-water supply is equally variable. In fact the habits of each person determines largely what his total consumption of heat will be. What, then, is the object in giving particulars of one case only unless one also gives elaborate details of the way the apparatus is used? I tried in a book I wrote some few years ago, called "Domestic Fuel Consumption," to give an estimate of the amount of heat required by the average man for the several purposes in a year. How variable and uncertain any such estimates must of necessity be can be judged from the fact that a human being can easily get along in reasonable comfort, even in cold weather, without any heat supply whatever. I say this with confidence because I have myself done it. It has been most interesting to compare the figures given in this paper with my own estimate based only on a knowledge of the efficiencies of the various parts of the plant and on observations of the habits of the ordinary normal person. I give in Table A that comparison. The figures in cols. 1 and 2 are taken from my book. The other figures in the table are partly the author's and partly some obtained from very prolonged and extensive experiments of my own on various classes of buildings. The various items are calculated as follows:—The figures taken from my book were an estimate the basis of which is described at length in that publication. The figures derived from my own experiments were calculated as follows. The actual number of cubic feet of gas used for the several purposes throughout a year were observed by a special gas meter. The figure multiplied by the value of the gas and by the actual efficiency of the apparatus in use as previously determined in the laboratory gives the figures shown in the table. In the figures relating to "cooking" there were some corrections to make on account of the circumstance that the meter controlling the cooking-plant was also used for other boiling and water-heating purposes. The figures were derived from Prof. Smith's figures in the same way by determining the total heat in the electricity used and multiplying by an assumed value of the efficiency based on experiments on electrical cookers, etc., in my own laboratory. It is obvious that from such figures any person can calculate exactly what should be his cost per annum for electricity, gas, coke or any other means of heating, provided he knows his personal equation and that of his house, the price per unit and what is the efficiency of his cook and of the various parts of the plant which he is going to use. These questions of efficiency and rates per unit are at the root of the whole problem of cost; without them the whole question is in the air. One might as well try to lay down the weekly cost of food for one person. It depends on what he eats and how much he eats. It must be obvious, too, that the most economical results can only be obtained by determining in detail what is the most economical method of dealing with each separate item of consumption in the house, having regard to all the pertinent conditions. As the result of tests at my house I have come to the conclusion that the best combination for practical cooking purposes is a gas hot-plate and electric oven with a gas preheater or booster for the oven. Such a

TABLE A.

Net B.Th.U. used per person per annum.

	Prof. Barker's estimate (From "Domestic Fuel Consumption")		From Prof. Barker's experiments (one person living alone)	From Prof. Smith's figures	From Mr. B. Hague's figure
	Well-to-do person	Artisan			
	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.
Heating	3 000 000	1 000 000	4 500 000	3 400 000	—
Hot-water supply and laundry ..	8 000 000	2 000 000	2 100 000	4 150 000	—
Cooking	400 000	180 000	800 000	474 000	—
Total	11 400 000	3 180 000	7 400 000	8 024 000	6 100 000

combination is, of course, impossible in an ordinary household, nevertheless a range in which the peculiar features of gas and electricity were both utilized would be immensely more valuable than either a gas or an electric cooker. An all-electric or all-gas cooking range is in my view much inferior to a combined one. Much more is this the case in a whole house. I regularly use in my own house electricity, gas, coke and coal for heating, solid fuel and gas for hot-water supply, and electricity, gas and solid fuel for cooking. I am sure that everybody who wants the best and most economical results would do the same if he had the chance. The general plan of my experiments has been somewhat as follows. I have the control of a well-equipped laboratory especially designed for making these experiments. I have taken the whole of the plant with which I have been concerned and have put them through as thorough a test as I knew how to make in the laboratory. After the completion of these tests I have these appliances transferred to experimental cottages which have been placed at my service by the London County Council and have equipped several of these in different ways so that the amount of fuel consumed can be accurately measured. I have taken readings for many years, and I have a vast mass of data and of readings which I am now endeavouring to co-ordinate.

Major E. O. Henrici: As my house in the London area seems very comparable in size with the house described in such detail, some figures from my experience may be useful as a comparison. The house is an old one, and the number of persons in the house varies, being generally seven or eight. The only coal used is in the kitchen range, and in an anthracite stove in the drawing-room (this is convenient, though not ideal by any means). Practically all other rooms have gas fires, and there is a gas cooker. Lighting is entirely by electricity, whilst an electric iron and a vacuum cleaner are run from the lighting circuit. The appliances are not of the most modern description—the lagging of the hot-water system is anything but efficient—and I have no doubt that the running costs could be considerably reduced by installing a coke boiler and a more modern gas cooker and scrapping the kitchen range. I have not, however, felt disposed to incur the capital expenditure involved in modernizing the arrangements. I have recently completed three years in the house, and the total running expenditure on heating and lighting for the three years ended Michaelmas 1925 has been £150, or an average of £50 per annum. This includes cost of repairs, lamp renewals, kindling, matches, etc., but does not allow for purchase and fitting of gas stoves, or any capital charges. The price of gas has varied between 9·8d. and 11d. a therm, and there is also a quarterly charge of 2s. for meter, and 6s. 1d. for hire of certain fires (the other fires are my property). These charges are included in the total expenditure for gas. Electricity cost 5d. a unit for the first two quarters, and thereafter 4½d. In both cases there is a charge of 2s. 6d. a quarter for meter rent. There is an alternative tariff available of 10 per cent on the rateable value, plus 1½d. per unit. The figures in Table B give my expenditure for each of the three years.

TABLE B.

Year ending Michaelmas	Gas				Electricity				Coal	Coal and miscellaneous cost			Total cost		
	Therms	Cost			Units	Cost									
		£	s.	d.	kWh	£	s.	d.	tons	£	s.	d.	£	s.	d.
1923	310	15	13	2	386	8	6	1	—	23	15	0	47	14	3
1924	428	19	2	3	430	8	11	3	—	25	8	6	53	2	0
1925	378	17	5	7	466	9	4	9	—	23	0	9	49	11	1
Total	1 116	£52	1	0	1 282	£26	2	1	25*	£72	4	3	£150	7	4
Average	372	£17	7	0	427	£8	14	0	8	£24	1	5	£50	2	5

* Of the 25 tons of coal 3 tons were anthracite. The 25 tons is the amount purchased. Between 1 and 2 tons was in stock at the end of the period.

The figures under gas and electricity are those paid to the undertakings, and do not include lamp renewals, etc. The total electricity used was 1 282 kWh, or an average of 427 per annum. This is less than the lighting figure given in the paper, but the difference may be accounted for by the difference in latitude of London and Glasgow. It will be seen from this that my figures for a year's expenses are about £6 higher than those given in the paper, but they include lamp renewals, matches, etc., which the author's do not. It is also worth remarking that with the tariff now in force in my district (Barnes Urban District Council) the cost of the energy used by the author would have been over £100 per annum. I have not inquired whether a special rate would be charged for a night load. I have made an estimate of the coal consumed in heating the house, whether consumed in the house or gasworks, and in my case it works out at between 9 and 10 tons, whilst in

the Glasgow case it is about 17 tons. The coal used in the generating station is, of course, of a cheaper quality than that used in the gasworks or in the house. During the winter almost the whole of the gas consumed in my house is used for "heating" and very little for cooking, and from my figures for December 1924 and January 1925 (nine weeks) I get a consumption of about 10 therms a week of gas, plus 11 therms a week of anthracite for heating my house. The corresponding Glasgow figure is 200 units, or about 7 therms, showing apparently that electrical heating is about 3 times as efficient in a thermal sense (counting from the energy brought into the house) as my particular combination of gas and anthracite. Comparisons of this sort must, however, not be taken too seriously, as so many factors vary in different houses. Generally speaking, it would appear that the cost of electric cooking and heating becomes comparable with that of gas plus coal when current can be obtained at ½d. a unit or less. Water-heating would appear to compare with an ordinary kitchen boiler at about 0·3d. a unit, but even at this price I am afraid it would not compare with a modern independent coke boiler and an efficiently lagged hot-water system. It would be interesting to know more about the capital cost of the installation in the author's house, and of the various appliances for cooking, heating, etc. Whilst there would certainly be a saving of labour were I to change to "all electric," the saving would not be very great, and would not be sufficient to enable any reduction to be made in the wages bill.

Dr. Margaret Fishenden: The paper enables very valuable practical comparisons of the costs of different methods of providing for domestic heating and cooking requirements to be arrived at. I do not propose to refer to lighting, as I believe it may be taken for granted that at anything like a reasonable tariff most householders would prefer electricity to gas for this purpose. The total cost of the energy used for all purposes in the author's 10-roomed all-electric house in a year's working was £43 8s., as compared with averages of £43 10s. for a slightly smaller house using coal, gas and electricity, and £51 for a slightly larger house using coal and gas—say a mean value of about £47. Major Henrici has shown that in a house closely comparable with that of the author's, but equipped with an old-fashioned kitchen range and back-boiler, a gas cooker, gas fires and an anthracite stove, the total cost of fuel and lighting, after deducting rent for meters and fires, was about £48 per annum, of which gas accounted for £15 15s., electricity for £8 4s., and coal, etc., for £24. In my own 10-roomed house, which is again dependent upon an old-fashioned kitchener with back-boiler for hot-water supply, but which has a coke-fired boiler feeding radiators in the hall and on the first landing, one open sitting-room grate burning coal, gas fires, a gas cooker and a small gas boiler, the bill for fuel and electricity has averaged about £44 for the past 2 years. Gas has cost £8, electricity (for lighting and one iron) £9, coal £22 and coke £5 per year. There are five people in the house. Whilst the figures quoted obviously depend upon the prices paid for the various fuels used, they are, without going into further detail, sufficient to show that where such tariffs for electricity as that available in Glasgow are offered to the domestic consumer, a house of moderate size can, with care, be run on electricity alone at a cost not exceeding that of coal, gas and electricity as ordinarily used. On the other hand, it shows equally clearly that electricity at prices exceeding 1d. per unit would be quite out of the running. These comparisons are with houses using coal-fired kitcheners with back-boilers for hot-water supply, a type of installation well known to be extravagant for establishments of the class under consideration, and although the total bill for electricity which has been quoted is no heavier than that of fuel in a good many houses where electricity is not used, except perhaps for lighting, it can be shown that by the substitution of more up-to-date appliances considerable reductions might be effected, especially in the cost of water-heating. When considerable quantities of hot water are required, an independent coke-fired boiler is generally the cheapest means of producing it. The cost of potential heat units in electricity at 0·44d. per unit, which is the very low price paid by the author for water-heating, is about 7½ times those in coke at 40s. per ton. Small independent boilers, as a rule, yield a water-heating efficiency of some 45 per cent, and even if an efficiency of 100 per cent is allowed for electric appliances they remain, on the basis of equal hot-water production, about 3½ times as dear as coke. In other words, the author's bill of £13 8s. 10d. for electricity might have been replaced by one of less than £4 for coke, a saving of more than £9 per annum. Normally there would be heavy storage losses due to inadequate insulation of pipes and cylinders, which would increase the amount of coke necessary, but such losses would apply equally to water heated electrically, especially overnight, were not special steps taken to prevent them. It is, however, a drawback of the coke-fired boiler that difficulty may be experienced in maintaining combustion at the minimum rate requisite. In this case, for instance, about 12 lb. of coke per day would produce sufficient hot water, and it is doubtful whether combustion could be maintained continuously at so low a rate. The fire could, of course, be run intermittently, which would mean increased labour and lessened convenience; or, alternatively, an extra amount of coke might be burned, and hot water used more freely. Even at double the consumption, which certainly need not be exceeded, there would be a saving of nearly £5 per year in comparison with electricity, and twice as much hot water available. This might be utilized for heating a radiator. For cooking purposes, if electricity at ½d. per unit is to compete in cost with gas at 9d. per therm, it must be used with about 60 per cent higher efficiency. The Gas Standardization Committee estimated that four times as much gas was used on the hot-plate as in the oven. There seems to be no reason why the proportion should be different for an electric cooker. Many tests have shown that well-designed and properly adjusted gas-rings will give an efficiency of 50 per cent in water-heating. On the prices quoted, electricity at 80 per cent efficiency would cost no more than gas. Self-contained kettles meet this condition, but the efficiency of the best types of commercial electric hot-plates is probably nearer 60 per cent. The author speaks of

efficiencies so low as 20–25 per cent, starting from cold, but these would appear to be unusually low. Dr. Fleming, in 1911, gave corresponding values of 46–47 per cent, the Swiss Association of Electrical Engineers 40–65 per cent and the Hotpoint Company 33–61 per cent, according to the type of hot-plate and cooking utensil used. For continuous use much higher values were of course obtained. If we take 60 per cent for electrically-heated and 45 per cent for gas-heated appliances, for hot-plate work electricity would be rather dearer than gas. On the other hand, however, electric ovens are, or ought to be, far more efficient than gas ovens, and for all-round cooking purposes electricity at ½d. per unit can probably hold its own against gas at 9d. per therm. For heating requirements there is no doubt that the portability of electric appliances is often a great advantage. The low amount of energy which sufficed for the heating of the author's house appears to afford an example of this. Heating may be considered in relation to (*a*) the entire house, (*b*) a single room, or (*c*) the occupants themselves. Practically all the heat which a fire or heater emits is ultimately used in warming one part or another of the house and its contents. But an amount of heat which would be totally inadequate to warm a whole house to a comfortable temperature might yet, if generated in, or led to, the right place, suffice to warm a single room; and an amount of radiant heat too small to bring a room to a comfortable temperature throughout might yet warm occupants situated directly in its path. For the further away from a fire are the occupants of a room, the less is the intensity of the radiation falling upon them; and the fact that an electric heater can be placed where desired, and moved as convenient, results in its practical effect being magnified as compared with a heater giving similar emission at a greater distance away. No one would contend that electricity is suitable for central heating; for the individual needs of a small family, the author's experience would appear to show that at ½d. per unit it can compete successfully with other methods. In the six months of heaviest consumption an average of only about 25½ units per day were used for heating purposes, or, at 100 per cent efficiency, a utilization of 87 000 B.Th.U. per day. About the same amount of energy would be emitted into a room from a single gas fire burning 30 cub. ft. of gas per hour, or by a single coal fire burning at an average rate of 2¼ lb. per hour, over a 12-hour day. In the months of December 1924 and January 1925, the thermal consumption of gas and anthracite for heating purposes in Major Henrici's house was 3 times that of the electricity used in the author's house; and this, assuming an efficiency of 50 per cent for gas fires and anthracite stove, indicates a heat liberation in the rooms 50 per cent in excess of that in the all-electric house. Presumably the portability of the electric heaters counterbalanced their deficiency in actual heat production, but it must be assumed that the temperatures maintained in the house were relatively low. I should be interested to hear whether this caused any discomfort. I believe that it is healthy to breathe cool air, but my experience has led me to the opinion that a room with very cold walls is uncomfortable. The reason for this is not far to seek. The human body maintains itself at a temperature of about 98° F. by the oxidation of foodstuffs. Consequently, in ordinary indoor surroundings, heat is lost both by radiation and convection. The temperature of a room may be so adjusted that the resulting rate of heat loss from the occupants is not excessive; or, alternatively, the effects of reduced temperatures may be counterbalanced by the absorption of radiation from a fire or other high-temperature source. Cold air increases the rate of heat loss by convection, whilst cold surroundings increase the rate of heat loss by radiation; and to sit near a high-temperature radiator in a room with very cold air and walls gives rise to a scorched-on-one-side, chilly-on-the-other, sensation. On the other hand, I should expect the panel heating which Dr. Ferranti has described to be extremely comfortable, as its effect is so much less concentrated than that of high-temperature radiators. Freely exposed warm surfaces, other than brightly polished metals, even at temperatures of only about 100° F. emit about one-half their energy in the form of radiation; and in panel-heating convection currents are further hindered on account of the layer of warm air in contact with the ceiling being already at the highest level attainable in the room. As regards the advantages of portability, tests made by Dr. Lulofs of Amsterdam, and published last year in the *Electrical Times*, are of interest. Electric heating mats, fixed to the forms in such a manner that the feet of the children could rest on them, were used in a schoolroom, and it was claimed that by thus producing the heat exactly where it was wanted, 0·4 unit of electricity became the equivalent of 1 lb. of coke in effective heating value. On this basis, electricity at ½d. per unit would cost only about two-thirds as much as coke. On the other hand, somewhat similar tests made by Wigersma in Haarlem, in which coke, gas and electricity were compared in schoolrooms of similar size, the heating being so regulated as to provide the maximum comfort, showed electricity at ½d. per unit to be about twice as dear as coke. On the basis of equal heat production it would have been four times as dear. The difference was attributed to the improved " space factor " with electric heating.

Mr. L. J. Gooch: From my own point of view and, I believe, from that of many other would-be users of electricity, the all-electric house is at the moment impossible, because the electrical engineer has not yet produced, to my knowledge at any rate, a fire which for comfort can be compared with a coal fire. From what the author has said it would seem that even in Glasgow the all-electric house does not show any very great financial advantage over the ordinary house, and in this connection I think it behoves the sales departments of electricity supply undertakings to bring forward the other merits of electrical working, many of which the author has pointed out. One is the possibility of switching a light on and off from various points. There are, of course, many other obvious advantages which, if brought to the knowledge of the general public, should go far towards the promotion of the use of electricity for domestic purposes.

Major H. Carter (*communicated*): I believe that I am right in stating that although we have previously had papers on this subject from the supply engineer's

point of view, this is the first we have had from the consumer's viewpoint. The former are always open to criticism from sceptics, as the propaganda of people with something to sell. The statistics and opinions of the man who pays the bill are much more convincing. For the same reason, I think it appropriate that my contribution to the discussion should represent the experience of a consumer, particularly so, since during the course of the discussion it has been broadly hinted that such joys as the author describes are unattainable in London. I hope that my remarks will at any rate show that in some districts in London very considerable advantages can be gained by the use of electricity for most domestic purposes, at a reasonable cost. For more than 3 years my house in Wimbledon has been practically entirely run electrically. The rates are :— Lighting 4½d., heating, etc., 1d., water heating (continuous load) approx. ¾d. per unit. The house is smaller than the author's to the extent of two rooms, and the household consists of six persons, including two young children. A coal fire is used in the living-room from mid-November to mid-April, electricity being used for all other purposes. I must admit myself to be an unrepentant advocate of a coal fire for continuous use in winter. The apparatus in use consists of :—6·2-kW Falco cooker of 1922 pattern, two 2-kW Belling fires, 300–600 watt 20-gallon Bastian storage geyser, kettle, vacuum cleaner and small appliances. During the year ending 30th September, 1925, my consumption was approximately 9 000 units for power and 300 units for lighting, the same proportion as that mentioned by the author. The cost of this was slightly under £41, to which must be added £3 8s. 6d. for 24 cwts. of coal. It should be mentioned in passing that this must be regarded as a heavy year due to an abnormal amount of illness. I am not in a position to make such accurate subdivision of costs as the author, but knowing the way in which the apparatus is used and comparing the consumptions for summer and winter quarters, I can arrive at a fair approximation which is not without interest, and which is shown in Table C.

TABLE C.

Purpose	Units	Cost		
	kWh	£	s.	d.
Heating	2 400	10	0	0
Hot water	2 600	9	0	0
Cooking and small purposes (including kettle)	3 900	16	5	0
Lighting	296	5	10	0
Coal	24 cwts.	3	8	6

It encourages me to notice that on the rates prevailing in Glasgow my bill would be reduced by £13, and leads me to look hopefully for some reduction in the future.

I give below some details of the apparatus used.

Cooker.—The only drawback to this is the well-known slowness of the boiling-plates. I have had a happier experience than Mr. Hague as regards maintenance. In 3½ years the only fault has been a blown fuse, due to a short-circuit caused by scale falling from the reflector plates fitted to the boiling-plates. The author mentions experiments with lighter grids. I presume he means the covering plates for the elements. I find in my household an irrepressible tendency to dispense with them altogether, and to place the utensils direct on the fireclay blocks.

Water heater.—The author seems to have solved the hot-water problem very satisfactorily, and produces an adequate quantity available for distribution through service pipes, at a reasonable cost. The comparatively small capacity of the storage geyser which I am using is its only drawback; in all other respects it is the most popular appliance in the house. The author's apparatus appears to be a little more efficient, as it produces about four times as much hot water at approximately the same temperature for about three times the current consumption.

Fires.—I have found a strange tendency for the elements to fail on the back of the fireclay block, where they are secured to the terminals, and I should like to know if this is a general experience.

In conclusion, I agree with the author that with energy at 1d. per unit it is well worth while for an average household to work electrically, provided a coal fire is retained for the living-room in the winter. I will not go so far as to say that I am getting my services in the cheapest possible way, but any extra expense is amply compensated by cleanliness, convenience and extra comfort.

Mr. J. Coxon (*communicated*) : The paper contains much information of inestimable value to electrical engineers in support of the more extensive use of electricity for household requirements. This all-electric house described forms, so to speak, a distinct landmark in the progress of electrification and points the way to that desirable ideal when the smoke nuisance, at any rate from open fires, will have been abolished. It shows the advantages to be gained by co-operation with the architect and the city electrical engineer, and demonstrates clearly an excellent way of improving the load factor of our generating stations. The success of the author's scheme is dependent upon the low rates in force in Glasgow for electricity and for the hire of apparatus. I think it is the high rates for electricity and the heavy cost of apparatus which more than anything else stand in the way of the more universal adoption of electricity. We all know well the diversity of rates which exists throughout the country and even in and around London. Generally it will be found that these charges are lowest in the manufacturing centres where the population is also the densest, and thus there is the tendency to attract more and more people to these centres, making matters worse and worse from a health point of view. To overcome this it appears desirable rather to attract manufacturers and all the population that go with them, to the rural districts, and one way of aiding this is to offer cheap electricity in these districts, such as is being done by the Shropshire, Worcestershire and Staffordshire Electric Power Co. at Stourport. As a further aid in this direction, and now that we have a central authority in the Electricity Commission, could not all electricity supplies be " pooled "

and a more uniform rate applied generally so as to decentralize the manufacturing districts? It is, further, obviously unjust that in one place electricity should be less than 1d. per unit and in another as much as 1s. per unit. The author says on page 297 that with energy at about 1d. per unit and a low tariff for water-heating, the cost of an all-electric house compares with that of a similar house using coal, gas and electricity. Such low rates are at present available in very few cases and it is neither possible nor desirable that we should all settle in the few large cities where they are available. I submit that before real headway can be made in the universal use of electricity we want (1) more "linking-up" of stations; (2) a more uniform system of charging for electricity and the hire of apparatus; and (3) the elimination of the small and inefficient generating stations and of the profiteers.

Mr. J. F. Driver (*communicated*): One appreciates the statement of the author that "The time had arrived when a professor of electrical engineering ought to have enough faith in his convictions and calculations to put them to the test." Two years ago I myself, who hold the position of head of the electrical department of an engineering college, did the same. The author's experiences will, I am sure, serve as a guide to both architects and consumers, who may be doubtful as to the fate which awaits those who "cross the Rubicon." My own experience is that three or more points should be provided in every room, but I do not agree with the author in having all plugs of 15-ampere capacity. The flash from a dead short-circuit on the flexible of, say, a vacuum cleaner, might be dangerous. In my house I have one or more 5-ampere plugs in each room in addition to the 15-ampere power plugs; the 5-ampere plugs are lightly fused and are used for small appliances such as electric iron, vacuum cleaner, kettles, toaster, hair dryer, bed warmer, etc. The method described in the paper for drying clothes is most interesting and merits the careful attention of architects. I suggest that makers of electric cookers are following gas-stove design in a much too slavish manner. Why, for example, is the exterior of the oven not polished to reduce radiation? I should be very glad to have particulars as to the manner in which the author improved the hot-plates on his cooker. My first electric cooker had hot-plates with the elements sunk in grooves in fireclay supports. Six months ago the makers agreed to change the cooker for one of their latest design. On this later cooker the hot-plates consist of open "spirals" with polished aluminium reflectors underneath. These hot-plates are a great improvement on the old, partly, I suggest, due to the reflectors and partly to the fact that convection currents of hot air rise to the cooking utensils. The objections to self-contained cooking utensils are their weight and expense. Steamers having one utensil above the other overcome the difficulty to some extent. Would it be possible to produce a closed heater, the top of which consists of a recess containing a low-melting-point alloy? Saucepans and kettles would then be placed into the molten metal, thus giving intimate contact. The author's method of overcoming the hot-water difficulty is of particular interest, but I suggest that a thermostatic cut-out on the tank is desirable. I feel that in many houses two smaller tanks would be better, and I should be glad of the author's opinion as to the relative merits of his method and the use of a storage tank of low wattage continually in circuit. In spite of all that has been said about the advantage of radiant heaters over convectors, I suggest that in cold weather warm air is desirable, and that low-power wall-pattern convectors are useful to "take the chill off the atmosphere," using the radiant heaters as boosters. I suggest that electrical contractors should be prepared to act as consultants to non-technical clients. One sees large numbers of new houses being wired in a totally inadequate manner. Once a house is built, the cost of wiring extensions is high. If a contractor would point out to clients the future developments likely to take place, I feel sure that more adequate systems of wiring would often be installed.

Prof. C. L. Fortescue (*communicated*): Interesting as the paper is, it unfortunately does not deal with the aspects of domestic electric power supply which are principally of importance at the present moment. As the author remarks in the opening paragraphs of the paper, calculations of the power consumption for domestic purposes are frequently made and the basis for these calculations is tolerably well known. In this connection it may be observed that, comparing the figures given for his consumption with the other data available, it is obvious that his household has been remarkably economical. It is probable that in a normal household where there is neither the expert supervision that he has given nor the keen interest in the experiment throughout the whole household, the actual consumption for heating and for hot-water supplies is likely to be much greater than in the author's house. Some 12 months ago it was necessary for me to investigate the possibility of the complete electrification of a house of very similar size to the author's but which had a rather cold aspect and was less compactly built than his. For this house the total consumption was estimated to be about 24 000 units per annum and, being in an outlying London district, the cost for power alone would have amounted to about £220 per annum against an actual expenditure of about £60 on a central heating plant with gas cooking, gas fires and electric light. In this case it proved impossible to justify this heavy additional charge, and unless power can be provided at very much lower rates than those available in this and the majority of other residential districts it does not appear that there is any real hope for a considerable extension of the domestic load. The real problem, therefore, as it appears to me, is whether or not the development of the domestic load at a price in the neighbourhood of 0·75d. per unit is a practical possibility. There is no doubt whatever that the demand exists, but to satisfy this demand would in all probability necessitate laying new cables throughout the residential districts, and it becomes a matter of calculation on the part of the supply undertakings as to whether a charge of 0·75d. per unit is an economic proposition. If the paper leads to questions of this kind being worked out and possibly to a further paper before the Institution giving some of the results of these calculations, it will have served a very useful purpose.

Mr. R. Grierson (*communicated*): Undoubtedly the author was fortunate in selecting Glasgow as the scene of his experiments, since his records show that the average cost per unit was 0·625d. for the house and 0·74d. for the flat. If this price could be obtained, in similar circumstances, throughout the British Isles, it is obvious that it would be necessary to divert the activities of the Electrical Development Association into some other channel. In domestic electrification schemes we have two serious difficulties to contend with: (*a*) the unconverted electrical engineer who says, with a wise smile, that the proposition is both uneconomical and impossible; (*b*) the consumer who has already tried electrical cooking and heating with current in the neighbourhood of 2d. to 3d. per unit, and has been very badly bitten. In his case, once bitten, twice shy. Exactly how each of these cases is to be dealt with it is difficult to say, but the fact remains that both form serious brakes on "All-Electric" progress. I entirely agree with the author's view, that each radiator plug should be standardized at 15 amperes and wired back directly to a local fuse board, and I should like to see a recommendation to this effect included in the Wiring Regulations of the Institution. Whilst it may be safe to wire two heating plugs to a circuit so long as the present occupiers of a flat or house remain, new tenants or owners will not trouble and it is almost inevitable that at some future date two fires, each rated for 3 kW, will be connected simultaneously. True, the fuse will probably blow, but it is also true, in all probability, that the fuse will be stiffened until it holds. I was particularly interested in Section (10) on Heating because the author has practically arrived at the "panel heating" stage of electric heating by a process of logical deduction and with an entirely unbiased mind. The author states that, broadly speaking, there are two alternative ways of heating to be considered, e.g. convection and radiation, and I would agree if he would further subdivide the latter into high- and low-temperature sources. I regard the ordinary electric radiator as the equivalent of an unshaded high-power gas-filled lamp, e.g. it gives rise to glare and shadows and, to be comfortable in a living-room, the occupant has to accommodate himself to the position of the radiator. The author has realized this and proposes two or three small radiators, or the equivalent of, say, four small lamps, to minimize the undesirable effects of high intrinsic brilliancy and to avoid harsh shadows. Anyone who has used a gas fire or an electric radiator (e.g. a small, high-temperature source) knows only too well the effect of these heat shadows, which are the cause of cold chairs, carpets and other signs of discomfort, i.e. he is made to appreciate the operation of the inverse square law. When children are present, and even if they are not, two or three radiators, with their flexible conductors, straggling across the room, are without doubt excessively inconvenient, apart altogether from their effect on the decorative scheme. The logical development of electric heating, as suggested by the late Mr. Wordingham, is so to locate and spread the warming surface that all "glare" and shadows are practically eliminated. I have found that if conductors are embedded in strips of the plaster ceiling and energy is dissipated at the rate of approximately 40–50 watts per sq. ft. of surface, the temperature of the surface of the ceiling is maintained at approximately 120° F. and the radiant warmth resulting therefrom is most pleasing and ensures a condition of comfort throughout the room. Further, due to the extended surface, the inverse square law no longer holds, and walls, floors and furniture either reflect the heat or absorb it and then re-radiate. Normally speaking, depending on construction, exposure, glass surface, etc., 10 sq. ft. of heating surface, or 0·5 watt per cub. ft. of space, is all that is required, so that in a room containing 2 500 cub. ft., 25 sq. ft. of panel surface would be required, say 12 ft. 6 in. × 2 ft. or 16 ft. 6 in. × 1 ft. 6 in. The maximum rating for this panel surface would be 1 250 watts for continuous use during extreme weather and, say, 800 watts for normal use. Due to the low temperature of the surface, the percentage of heat lost by convection is extremely small and, due to the location of the panels in the ceiling, this is still further reduced. Herein lies the secret of the marked economies and consequent low current consumption obtainable by the panel system, i.e. it is unnecessary to warm the air to any appreciable extent and hence the usual loss of heat, due to ventilation, is very largely avoided. Further, as the author states, experience shows with ample radiant heat an air temperature of 50–55° F. is very comfortable, whereas with warmed air 62–65° F. is desirable. As a matter of fact, the solar thermometer is a more reliable indication of comfort than the ordinary air thermometer, when the radiant method of heating is employed. Panel heating, using hot water as the medium, has been thoroughly tried out in such buildings as the Midland Adelphi Hotel and Royal Liver Buildings, Liverpool; Magnet House, Bush House and Australia House, Kingsway; the Banqueting Hall, Wembley, and Messrs. Harvey Nichols of Knightsbridge, and it is now being installed in Devonshire House, Messrs. Thos. Cook and Sons, and Messrs. Swan and Edgar's, Piccadilly. Records prove that the fuel consumed is 66 per cent of that used in the hot-water radiator system, due to the facts enumerated above. When electricity is used as the heating medium the cost of maintenance is nil, since due to the low operating temperature of the conductors (approx. 150° F.) no deterioration takes place, i.e. there are no elements to renew. Clearly the panel method of warming should be of great interest to all electrical engineers, as it places in their hands a really practicable and economical method of employing electrical energy for heating purposes. The most recent installation, available for general inspection, is at the Cinema de Paris, in Charing Cross-road, the total connected load being 30 kW. Regarding the economic possibility of "all-electric" houses in connection with Government housing schemes, I recently addressed a questionnaire to some 30 members of my staff and employees, inquiring the total amount paid by them for coal, gas and electricity for heating, lighting, cooking and hot-water supply purposes. The replies indicated that the majority resided in 5-roomed houses or flats, i.e. living-room, parlour and 3 bedrooms, and the average total amount paid was £16, the maximum being £19 12s. and the minimum £13 5s. The weight of coal

used in the living-room range averaged 2 tons, and if this is priced at £5 it means that for this class of house the average family has approximately £11 or 2 640d. to spend on electrical energy. The number of units or kWh available for £16 or 3 840d. and also for the above sum, at different average costs per kWh, is shown in Table D.

TABLE D.

Pence per kWh	1·00	0·875	0·75	0·625	0·50
"All-electric" (£16 or 3 840d. per annum)	3 840	4 400	5 120	6 150	7 680
With coal range (electricity £11 or 2 640d. per annum)	2 640	3 020	3 520	4 220	5 280

Averaging the estimates for the annual consumption of electrical energy (kindly supplied to me by the Electricity Departments of Marylebone, North Tees, Hackney, Gateshead, Woolwich and Glasgow) a figure of 3 500 kWh per year is obtained. (These figures practically all apply to houses fitted with a modern combined water heater and cooker fixed in the living-room.) It would therefore appear that if the all-electric scheme is to be applied successfully to the Government type of house, the average price for electrical energy must not exceed 0·75d. per kWh.* It is useless, in my opinion, to talk to the man who earns £4 per week about the labour-saving and other advantages to be derived from the use of electrical energy, if it costs him more than his present method, since he has not the surplus cash to pay for the advantages.

Mr. A. F. Harmer (*communicated*): In the introduction the author compares (comparisons are always odious) modern electrical apparatus with Early-Victorian coal grates. Blackleading is unheard-of now, and, as regards pollution of atmosphere, I have proved, with a modern coal grate which I fitted a year or two ago, that the decorations keep cleaner than those in the adjacent room which is entirely electrically heated; in my opinion this is due to the fact that all floating dust is carried up the flue and is not distributed around the walls, etc., in a circular manner as with the electrical heater. On page 298 the author states that "cut flowers may last a month or even longer." Here again I find that flowers last longer in the coal-heated room, due, no doubt, to the much better ventilation; the coal fire is, of course, an open one. The author makes a great point about garbage disposal, but neither I nor anybody I know have ever used the coal fire for this purpose, especially, as the paper seems to indicate, the sitting-room grate. Local methods of collection have always been very efficient; moreover, refuse collection is included in the rates. Regarding Section (7) "Cooking," I have yet to learn that a strong cabbage boiled electrically smells any more attractively than when boiled on a coal fire, rather the reverse in fact, as there is no flue to carry off the odour; all my cooking is done electrically. The remarks "educated and refined women . . . make cooking attractive to many intelligent people" I find particularly uncalled for; surely any woman worthy of the name takes a pride in cooking, however done. Of course, if electricity is converting "educated and refined" females into true women, then we engineers have something still further to be proud of. I am sufficiently enthusiastic for the future of electricity to believe that it will "get there" without the aid of such very dubious and antiquated comparisons as the author puts forward. I note that he thought it advisable to arrange flues for ventilating purposes; electrically-heated rooms without flues are insufferable. I agree that the human body appreciates the heat (and light) rays of the sun or glowing fire; for this reason I have replaced all my "hot-wire" heaters with the old-fashioned (but the best) lamp radiators. On page 289 the author says "the house was built to be a home and not a showroom," yet in Fig. 4 he illustrates the most appalling fuse-redundant distribution board that it would be possible to make. Four, and not 31, ways would have been sufficient. In conclusion I give the total annual costs of heating and cooking in a 6-roomed cottage, in the district where the author used to reside, and where I have endeavoured to use as much electrical apparatus as possible, consistent with economy and comfort. All cooking and lighting is electrical; water is gas- and coal-heated; heating is coal and electrical. I have had to give up the use of motors for domestic purposes owing to a separate and higher rate for current, together with the nuisance of an extra meter.

Apparatus:—4½-kW cooker, separate small grill, toaster, iron, kettle, and 5 heaters. Lighting—25 points.

Costs:	£ s. d.	
Coal (2 tons)	4 14 6	
Gas	1 10 0	at 3s. 8d. per 1 000 ft.
Electricity—		
Cooking and heating	3 14 2	at 1d. per unit.
Lighting ..	2 6 6	at 4½d. per unit.
	£12 5 2	for the whole year 1924–5.

For the year 1923–4 the total units were 1 per cent higher.

The lighting voltage is 25, consequently I have not found it necessary to renew any lamps since 1913 (12 years); some still in use date back to the time when metal filaments were first made.

Mrs. M. L. Matthews (*communicated*): Some time ago I made inquiries as to the cost of installation of electric light in my house and was informed that it would be roughly £60. In such a case the problems with which the housewife is faced are as follows:—

* Since this figure was calculated it has been stated in the *Electrical Review* that tests taken in all parts of the country show an average of 5 350 kWh for the all-electric and 4 166 kWh for the one-coal-fire 5-roomed house or flat.

Is the sinking of such a sum justifiable in view of the possibility of the yearly bill for heating and lighting being increased ? Will the appreciation of the property due to the installation, and the reduced maintenance charges, offset the expenditure ? In the event of the house being sold, is it likely that the purchaser will take over the installation, and, if so, at what depreciation ? Also, she may have a conviction that manufacturers will revise all their ideas of cooker and heater designs. She does not know the answers to some of the questions I have raised, but she does know that she would enjoy the comfort, the cleanliness and labour-saving healthfulness of even a modest electrical outfit, to say nothing of washing machines, vacuum cleaners, etc. The present-day value of my house is £1 000, rental value £56 and rateable value £40, and the foregoing represents the electrical position of many thousands of its type over a very large area served by the electricity supply undertaking I have in mind. Surely supply undertakings could arrange to have sufficient capital available to enable them to let out on hire an adequate supply of electrical heating and cooking apparatus to prospective customers on such terms as would provide an equal division of the risk. At present the tendency of undertakings seems to be to encourage the consumer to buy the apparatus while they reap the returns in the payments for current consumed.

Mr. F. Tremain (*communicated*) : Has the author considered the provision of a fixed vacuum cleaner with convenient outlets on each floor for the attachment of hose ? I have been very desirous of providing this facility in my own house, which is similar to a very large number of two-storied villas now being erected, but the cost of such appliances, used in the smaller cinemas for instance, was prohibitive. I have not got further than providing the foundations on the promise of an engineering friend to produce a suitable small machine. Pressure of more profitable business has, however, prevented progress beyond the design of the machine and the production of castings. The machine would have been placed under the stairs and only about 9 ft. of metal pipe would have been required to reach the first (and only) upper floor. The estimated cost in quantities was £25 to £30, including a ½-h.p. motor. Exhaust was designed to be in the adjoining side entrance and would overcome the objectionable, if not injurious, odour experienced with most portable cleaners using a bag. As regards heating and hot water, I am of the opinion that in cold weather some form of preheating is essential. High charges for power in my district drove me to the installation of an " Ideal " domestic boiler, and to tolerate one coal fire. The smallest size boiler stoked with No. 3 washed coke, and kept going day and night with very slow combustion, provided for more hot water than is required in a small household. The difficulty is to keep the fire going slowly enough to prevent the water boiling, which is objectionable. These boilers should therefore be associated with at least one radiator near the front door so as to heat the air entering that way, as the boiler fire heats it from the back of the house. In my conservatory a small 600-watt workshop heater with three-heat control maintains a temperature of 40–45° F. when it is freezing outside and lessens the duty on the 2-kW radiator in the drawing-room, so that only half the heat available there is as a rule required. As the cost of running the heater is only 1s. 6d. a week at 1¼d. per unit this arrangement is economical. Two geysers are used loaded at 6 and 5 kW respectively in bathroom and scullery, but are not used simultaneously. The former provides a 10-gallon bath in about 15 mins., raising the water 50 deg. F. for about 2d., and the latter raises a gallon of water 50 deg. F. in 1 minute—costing about half a farthing. My total costs for heating, cooking, geysers (5 months in the year) on a rateable value of £47 are about £23 a year, including coal and coke. Were I fortunate enough to live in a neighbouring district, or with a two-part tariff, the cost would be under £20 a year. It should perhaps be added that during nearly 2 years' use the costs for renewals were nil, whilst the total equipment provides a maximum load of 0·75 kW for lighting and about 25 kW for other purposes.

[The author's reply to this discussion will be found on page 328.]

South Midland Centre, at Birmingham, 2 December, 1925.

Mr. F. J. Moffett : I presume that the fixed charge given by the author, viz. £12 10s. per annum, is intended to be the equivalent of the kilowatt maximum demand. In the author's " all-electric " house the maximum demand will be far higher than in the ordinary house in which lighting forms the major portion of the load, since in addition to the consumption of units for lighting there will be a heavy consumption for heating and cooking. Would the tariff be profitable to the supply authority if many consumers had a maximum demand of this value ? On page 298 the author states that the coal burnt at Dalmarnock generating station for each unit delivered at his house may be taken to be 2·24 lb. This means that the thermal efficiency from coal bunker to electric fire is roughly only 12 per cent. If an ordinary coke-fired hot-water boiler were used for the heating and hot-water supply, the thermal efficiency would be 5 or 6 times as high, say 70 per cent. A large proportion of the 16 or 17 tons of coal could therefore be saved, since the bulk of the author's current consumption is for heating and hot water. Incidentally the cost of heating and hot water would be lower. It does not appear to me that from the point of view of economy of fuel the use of electric energy for heating is justified. Raw coal is used in the generating station, but in a hot-water boiler such as that described above, coke can be used quite efficiently, thus enabling the gas and other valuable products to be utilized.

Mr. E. J. Jennings : The benefit to the supply undertaking of a steady night load, such as is called for in a hot-water scheme, cannot be exaggerated, and at ½d. per unit should yield a good profit. The drying

closet is very ingenious and should appeal strongly to the housewife. Cooking by electricity has been proved in every case to be an unqualified success, and even at 1½d. per unit is making headway in Birmingham. Undoubtedly the "all-electric" idea can only be properly developed with a two-part tariff. In Birmingham we are experimenting with two alternative tariffs of a two-part type, one being the ordinary rateable-value basis, and the other having the capital and fixed charges based on the assessed lighting requirements; in both cases the running charge will be ¾d. per unit. We are just at the point of completing our experimental period of one year, and when the figures have been considered there is every probability that a two-part tariff will be adopted in this city early next year. The paper is a valuable contribution to the question of development of the domestic load, but the author gives no information as to the first cost of equipping his "all-electric" house. The first cost of equipment, and wiring on such an elaborate system, must have run to a considerable figure and further information on these points would be of interest. I doubt whether many would be prepared to put so complete an installation in houses that are already built; the upheaval and expense would be too great. There is a danger in pushing the "all-electric" idea too far. It might be wiser in the long run to allow for one coal fire, and use electricity for cooking and partial heating, rather than risk dissatisfaction by going out for entire domestic electrification in the first instance.

Mr. W. Wilson: The paper is particularly valuable because the author has "gone the whole hog," in contradistinction to the great majority of users of domestic electricity. In my own case, although I have equipped the house for electric cooking as well as lighting and a certain amount of heating, the lack of a suitable tariff has prevented the adoption of a complete heating scheme and hot-water supply; the charges being made according to the author's second scheme, but with a price per unit averaging just three times that imposed in Glasgow, even without taking into account the extra low night rate there. My experience, however, fully endorses the claims and recommendations of the author; and it is very much to be hoped that other supply undertakings will follow the good example of those in the vicinity of Glasgow, by adopting a two-part tariff, with figures approximating to those quoted in the paper. With regard to water-heating, I have known this problem to be solved fairly satisfactorily about 15 years ago by a supply undertaking which agreed to charge a comparatively low flat rate for a 600-watt heating element; this was inserted in an ordinary domestic hot-water cylinder and kept continuously switched on for 24 hours a day throughout the year. There is no doubt, however, that the arrangement arrived at jointly by the author and the Glasgow Corporation is the most satisfactory that can be imagined, and when its general adoption is facilitated by those responsible for our power supply it will remove the last difficulty in the way of the "all-electric" house. The opinions expressed by the author to which I should like to accord the strongest support are those dealing with the design of cooking apparatus. I agree entirely that our oven designers are still copying an older apparatus the features of which are dependent upon its having to be stoked with coal and placed so that its hot hob can be accessible for cooking utensils. A discussion was held on the same subject in connection with a paper * by Messrs. Griffiths and Schofield and in the discussion thereon I made some remarks, which need not be repeated here, advocating an improvement commended by the present author. During his reading of the paper he showed a sketch of a cooking bench designed for self-contained apparatus, and I hope that he will publish this illustration in the *Journal*. This method is such as to employ to the full the peculiar advantages of electric cooking, and will save a very large proportion of the power lost, due to the avoidance of the use of the hot-plate. The latter is probably the worst piece of electrical apparatus used for any purpose. It is extremely wasteful, as was shown in a test that I carried out recently in which the amount of current used to boil a kettle was exactly four times as great with the ordinary hot-plate as with the self-contained electric kettle. It is also almost impossible to tell when it is switched on, and there is therefore the certainty, at any rate when operated by a domestic servant, that it will be left connected to the circuit quite frequently after the cooking utensils have been removed. I observe that the author specifies open hot-plates, and in this I again agree with him. They are more efficient than the ordinary closed pattern, and they do give some indication as to when they are in operation; but I am convinced that the correct procedure is to avoid the use of any hot-plate as far as possible, and to employ self-contained electrical apparatus, such as the kettle, saucepan and frying-pan. Two objections to the use of these are advanced by those concerned in producing electric cooking plant. First, they say that domestic servants are accustomed to washing ordinary cooking utensils in a bowl of hot water, and they cannot be prevented from treating the electrical apparatus in a similar manner, with the result that the insulation is spoiled. The other objection is that most utensils have to be inverted when their operations are finished in order to empty them of their contents; and that the electric utensil is unduly heavy for the purpose. The first argument I regard as frivolous, whilst the second, if it is of importance, should be met by the design of lighter heating elements. Neither objection should have sufficient strength to prevent the adoption of this type of apparatus, and the securing thereby of increased economy, rapidity, cleanliness and convenience. It is my opinion that the accusations of expense so generally made against electric cooking are almost entirely due to the use of the hot-plate, for the economy of the electric oven is well known, and was in any case proved by Mr. H. Gray in his paper † read in 1911. With regard to the details of the wiring, I am not altogether in agreement with the author's methods, although this may be a matter of opinion. My own preference is for screwed-conduit construction, which is perhaps due to a long residence in a country with a dry climate, where the methods advocated by the author would not be permitted on account of fire risks.

* "Some Thermal Characteristics of Electric Ovens, and Hot-Plates," *Journal I.E.E.*, 1921, vol. 59, p. 361.

† "Electric Heating as Applied to Cooking Apparatus" *ibid.*, 1911, vol. 47, p. 249.

Mr. H. Joseph: I am able from my own experience to confirm the general result of the author's figures. I have at various times used electricity (*a*) for lighting only, (*b*) for lighting and heating, and (*c*) for lighting, heating and cooking. I have not, however, had an opportunity of trying it for water-heating and I do not intend to do so until I can obtain a tariff approaching that which the author enjoys in Glasgow. I have come to the conclusion that whether coal, gas and electricity are used for the three services or whether electricity alone is used, there is very little difference in the cost, but that the last is infinitely preferable for all other reasons. For water-heating, however, it must be admitted that, in spite of all that the author has said, an economical kitchen range with an efficient boiler or a self-contained circulating boiler is difficult to improve upon. An unlimited supply of hot water is available at all times at a very low cost both in fuel and initial outlay. I should like to ask the author why the "all-electric" house is deemed not to require a scullery and why the washing and cooking must be done in the same room.

(*Communicated*): When the author says that only 3 to 4 per cent extra capital cost is entailed as a result of his all-electric equipment my feeling is that this is only correct because his building costs were very heavy owing to special requirements in various directions. Whilst congratulating him on what is no doubt a perfect equipment, it must be said that, where money is no object, perfection is not difficult to attain. If, however, such a service as he requires demands, in some cases, four or five power circuits in one room, one 20-way, one 8-way, one 6-way and two 3-way distribution boards in a comparatively small house, then he is putting the proposition beyond the reach of the majority of people.

Mr. R. H. Rawll: The author refers to a two-part tariff for residential purposes in operation in Glasgow. This tariff consists of a fixed annual charge and all the units consumed both for lighting and power are charged at one rate. I am of the opinion that consumers in general will look upon such a tariff very much more favourably than having to pay different rates for lighting and power. The average consumer cannot understand the fairness of such a method of charging as the latter, and any tariff which will increase his confidence in the supply undertaking serving him with current should certainly be encouraged. The co-operation of the architect and electrical engineer in the design of a house is very essential if electricity in the home is to develop along correct lines, and the author very rightly lays stress on this consideration. In this connection I should like to point out that only in a very small percentage indeed of the houses being erected to-day is a definite place alloted to the fixing of the supply undertaking's service apparatus. In most cases we have to hide them away inside pantries, etc., or else place them in sight in halls or rooms, where, even if they are enclosed by boxes or cupboards, they still constitute an eyesore, apart from taking up valuable floor-space which is an important point considering the limited space available in modern houses. I am glad the author makes a point of having the distribution boards fixed in an accessible position. In an extraordinary number of houses the fuse boards are located either high up near the ceiling or else tucked away in dark recesses, so as to make the replacement of a fuse a matter of great inconvenience and difficulty. The author states that since the cost of energy for lighting purposes is relatively small the cost of the lamps is an important factor, therefore it might be a sound policy to run lamps at less than the rated voltage. I do not quite follow his reasoning on this point. Does he mean to imply that a 260-volt lamp is cheaper than a 250-volt lamp of similar candle power (the pressure in Glasgow being 250 volts, I believe)? Personally I should think there is very little difference in price. Reference is made in the paper to the advisability of research and investigation into the possible utilization of separate cooking utensils each with its own self-contained heating element. This is certainly a matter on which research is necessary, and in this connection I should like to see a greater recognition on the part of electric cooking apparatus manufacturers of the point of view of the womenfolk. We electrical engineers may design cooking apparatus, but, after all, the ladies have to use them. Perhaps the newly-formed Electrical Association for Women will provide a channel for the useful discussion of this subject. The author prefers the storage system of water-heating with immersion heaters to the installation of several electric geysers in various parts of the house where hot water is required. I agree with him for the reasons he has stated; but there is another decided disadvantage of the use of electric geysers from the supply undertaking's point of view. These geysers are usually of the order of 6 or 7 kW, and since they are used only for a few minutes at a time the switching on and off of such apparatus causes a considerable fluctuating pressure on the network, with the resultant flickering of the lamps connected thereto. Main engineers do not mind constant loads, however large, but what they do object to is the rapidly changing load, and therefore the storage heating system has their decided approval and preference as compared with the geyser principle. I agree that the installation of a few small radiators is more effective as regards warmth than one large radiator. It must, however, be borne in mind that the disposition of the furniture in a room often precludes this method being adopted; the cost of the duplication of heating appliances is another serious disadvantage. It is true that the heating load will reach its maximum in the evening in winter, but I cannot agree that since this occurs after the afternoon peaks the domestic heating load is not troublesome to the power station. Although at the afternoon peak the domestic heating load has not itself reached its maximum value, yet it is quite large enough to make itself very seriously felt on the network. Fig. 8 shows the load curve for 24 hours in the summer. The average load appears to be in the region of 7 amperes with occasional kicks as high as 30 amperes. It would be interesting if the author could give the corresponding figures for the winter, when the radiator and other heating appliances would be in circuit. The author appears to have been very fortunate in inducing the Glasgow Corporation to take all his load on a 2-wire service. In most residential net-

works such a load as the author takes, if connected to one outer conductor only of a 3-wire system, would cause a most inconvenient out-of-balance current in the neutral of the distributor, and to avoid this the load would be balanced as evenly as possible across both outers of the system. The author does not mention a new form of electric heater which has recently been placed on the market. This consists of a resistance wire in the form of a long solenoid fitted into a steel tube. These tubes are made in various lengths and take approximately 60 watts per foot run. They have been found very useful in keeping the temperature of a room at a pleasant heat, and for such purposes as towel-drying rails, etc. They are, of course, examples of the convection principle of heating but, as far as I know, they are not as oppressive as the usual hot-water system.

Mr. A. S. Dean: One aspect of the subject which has not been dealt with is the possibility of applying the electric principle to artisans' dwellings. The Housing Society with which I am associated has just completed the first part of an experiment that will be of interest. The society has built by direct labour three houses to precisely the same plan and specification except in the matter of details affected by the installation of electrical appliances. In one case the house is of the ordinary type with electric light only. In the second case one coal fire with hot-water circulation attached is provided, other heating, lighting and cooking to be done by electricity; in the third case the house is "all-electric." The first comparison of the cost of construction was made before adding the cost of any electrical appliances or even the wiring for electric light. The variation in cost of the foundations up to the damp course, owing to the difference in site-levels, was allowed for and the costs of combined drains were also averaged. The result at this stage showed that the "all-electric" house is considerably the cheapest, leaving a generous margin between its cost and that of the ordinary house for the provision of electrical appliances. The second part of the experiment will consist in estimating as accurately as possible the costs of running these houses. The City of Birmingham Electric Supply Department has consented to hold a demonstration in the "all-electric" house daily for the period of a week, and during the demonstration to obtain figures of consumption that will, no doubt, be of considerable value. The society had realized the many apparent advantages of what is termed the "all-electric" house, but as reliable figures as to cost and expense of running were not available in this district it was thought that an experiment might usefully be made. The comparative figures of cost of construction, cost and type of electrical equipment installed, and the estimated running costs will be published in full in the near future. Whether the society will be able to build any considerable number of houses of this nature will depend to some extent upon the cost of electricity.

Mr. A. J. Milne (*communicated*): Realizing the many apparent advantages of what is termed the "all-electric" house, and reliable figures as to building and expense of running costs not being available for Birmingham, it was thought that an experiment should be made. The result of the first part of this experiment I am able to publish by the courtesy of Mr. A. S. Dean, Secretary of the Woodlands Housing Society, Ltd., Bournville, which Society undertook the building of the various houses. The second part of the experiment will take the form of a comparison of records of the costs of running the different types of houses over a period of 12 months. These figures are not yet available. The houses are what is known as the "subsidy" type, the purchase price of the "all electric" house being £500, inclusive of electrical equipment. Building by direct labour, three houses were erected to the same plan and specification except where details are affected by the installation of electricity. In the first case the house has ordinary coal fires with gas laid on for a gas cooker, and to bedroom fireplaces for gas fires if required. Electric light only is installed. In the second case the house has one coal fire in the kitchen, with hot-water circulation attached to provide water to sink and in bathroom. All other heating, lighting and cooking will be done by electricity. In the third case the house is "all electric." These houses have the same accommodation, which includes a large living-room 16 ft. 5 in. by 11 ft., combined kitchen and scullery, and three bedrooms: also a bathroom upstairs. It might be noted here that in the case of the electric house considerable extra space is available in rooms which have no chimney breasts.

Building costs.—As to the question of cost of construction, the first comparison should be made without including the cost of electric appliances and wiring for electricity. It has been thought advisable to take an average of the cost from damp course in each case, thus making allowance for the variation in site-levels. The average cost of combined drains is also taken for the same reason. When the experiment was put in hand it was decided, as the "one coal fire" house and the "all-electric" house were to be built as a pair, to provide a chimney for a coal fire in the kitchen in both houses. A flue would thus be available in case the "all-electric" house should prove a step too far in advance of the existing demand for electricity. It is certain, however, that in the near future the cost of electricity in Birmingham will be such as to make this type of dwelling an economic proposition. Allowance has been made for the flue in arriving at the cost of the "all-electric" house. Table E shows the variation in cost of the various items and it should be borne in mind that some of the variations are probably due to the different time taken by different men to do parts of the work and that there has been a slight variation in cost of some of the materials. It has not been thought necessary to give actual total costs. Instead of giving the pounds in hundreds, tens and units, only the units are shown, which in total show the actual difference comparatively as regards net increases or decreases. The saving in cost on the ordinary house with electric light only in the case of the "one coal fire" house is therefore £20 16s. 2d., and £66 2s. 4d. in the case of the "all-electric" house. In explanation of Table E it should be specially noted that the remaining building costs, not given for various reasons, are common to all the types of houses referred to and do not affect the net saving or net increase in costs.

Layout of houses.—No mantelpiece or overmantels are provided in the case of the " one coal fire " and " all-electric " houses. Air bricks are arranged for in each room. The distribution board, etc., are fitted in a cupboard beneath the stairs.

Wiring.—The wiring has been carried out in screwed conduit. In the kitchen switch-sockets are provided for radiator, iron, kettle, etc. Pilot lamps are in circuit with the cooker, wash boiler and hot-water geyser. In the living-room, points are provided for radiator and table lamp. A radiator plug is fitted in each bedroom.

Lighting.—One 100-watt gas-filled lamp carried in an enclosed unit gives the requisite amount of light in the kitchen. The living-room is lighted by a 12-in. bowl fitting carrying a 100-watt lamp. The stair lights can be controlled from the hall or the landing. In the principal bedroom two lighting points are provided. A ceiling switch is included, so that the main light can be independently controlled from the bed. It is also arranged for the radiator to be controlled from the bed. One lighting point is provided in each of the other bedrooms and the bathroom.

Clothes washing.—A wash-boiler with 3-heat control is installed. The washer is rated at 3 kW and consists of a tinned copper container lagged to avoid heat loss.

Cooking.—A cooker will be hired from the Corporation of Birmingham Electric Supply Department. These cookers are of the usual type, the oven being surmounted by grill and hot-plates.

Hot water.—In the case of the " all-electric " house, a 15-gallon hot-water storage tank provides hot water for the bath and wash basin. The tank is fitted with a ball valve at the top. This operates in an entirely independent chamber, which is heat-insulated from the main bulk of water, and consequently is not working under disadvantageous conditions. The tank is fitted with a small constant heater (300 watts) and a separate booster heater (2 kW), the latter being of the combined switch and immersion-heater type. The 300-watt loading is sufficient to raise 18 gallons of water through 100 deg. F. in 24 hours. An independent geyser is installed for use in the kitchen; this is fitted over the sink and is connected by means of a flexible tube to the cold-water supply, when required. With regard to the " one coal fire " house, it can be arranged, if desired, to fit a 3-heat control auxiliary electric water heater, so that hot water can be obtained either by (1) the coal fire range only; (2) electricity entirely; or (3) a combination of both methods.

Heating.—The following are provided: A 3-kW radiator with 3-heat control for use in the living-room; a 2-kW portable fire with a 1-kW boiling ring attached for use in the kitchen, and bedrooms in case of sickness; and a small bedroom radiator. As a general guide it is necessary to allow 1–1½ watts per cubic foot of space. No definite rule can be laid down as, for instance, a bedroom is not usually required to be so warm as a living-room, and further, a great deal depends upon

TABLE E.

	Case 1 Electric light only	Case 2 One coal fire	Case 3 All electric	Remarks
Labour.	£ s. d.	£ s. d.	£ s. d.	
Brickwork—general ..	3 10 8	1 2 8	– 1 0 8	Distinct saving
Carpenter and joiner	6 6 1	3 11 10	3 11 10	Distinct saving
Plumber and gas fitter	3 16 2	3 5 2	3 5 2	Note slight difference
Plasterer	4 0 5	8 2 2	8 2 2	—
Painter and glazier ..	9 17 9	10 19 6	10 19 6	Cause of variation doubtful
Tiler	4 6 0	3 4 5	3 4 5	Cause of variation doubtful
Materials.				
Brickwork	14 10 0	8 0 8	– 3 0 0	1 000 bricks saved in each electric house
Joinery	3 12 6	8 6 3	8 6 3	—
Painting	7 0 7	6 2 10	6 2 10	—
Plumbing	6 13 8	– 2 4 0	– 19 14 0	(1) Includes gas boiler
Plastering	5 10 3	6 11 8	6 11 8	—
Ironmongery ..	4 19 11	4 10 0	4 10 0	—
Grates	22 17 6	14 12 2	—	Actual cost
		78 9 4	54 13 10	
		– 2 4 0	– 23 14 8	
	£97 1s. 6d.	£76 5s. 4d.	£30 19s. 2d.	

the number of doors, windows, etc., in the room. It is false economy to install a fire of too small power; it is much more economical to switch the radiator "full on" for a short time and maintain the temperature by cutting down the heating units, as one can so easily do with electricity. For large rooms it is advisable to install one or more radiators to give a better distribution of heat.

Running costs.—As already stated, sufficient data have not yet been collected to give definite running costs, but it is anticipated that the average weekly consumption of the "all-electric" house will be of the order of 100–120 units, and 80 units in the case of the "one coal fire" house.

Conclusion.—Although in many cases the "all electric" house has proved to be both popular and economical, its adoption will naturally depend very largely upon the tariff offered by the local electric supply undertaking. In Birmingham, with the present tariff, the "one coal fire" house is undoubtedly the most popular and is economically sound. As a guide to those who are desirous of converting their present electric lighting system to an "all-electric" installation, it may be noted that the cost of changing over the house with electric light only, referred to above, is £22 10s. if carried out in screwed tubing and vulcanized rubber cable; and £16 15s. if wired with lead-covered cable. The saving in decorations, cleaning, etc., need hardly be enlarged upon.

[The author's reply to this discussion will be found on page 328.]

North Midland Centre, at Leeds, 8 December, 1925.

Mr. S. D. Jones: The housewife, the manufacturer, the contractor, and the supply engineer are all deeply interested in this question. The author says nothing about the cost of installation, and whether such cost would be practicable in the general run of houses. It is to be noted that the author's is an "all-electric" house. Many people are now talking of electric houses with one coal fire. In Bradford they are claiming to reduce the smoke nuisance by having only one fire, forgetting that most working men have only one fire in their houses. Thus if they still have one fire the smoke nuisance would still be as bad. Then there is the question of heating houses, i.e. whether it should be by hot-water radiation or electric radiator. The question of the diversity factor in different neighbourhoods, in suburbs or in working-class districts is, I believe, a very important point. Fairly large houses like the author's will, as a rule, be surrounded by a fair amount of ground, and that will bear on the question of mains necessary to supply a district of such houses, as more and longer mains will be required. Would it not be a good proposition to have all-electric houses in working-class districts where the current density of the mains will be greater?

Mr. R. M. Longman: I was originally induced to use an electric cooker because of the smell which my gas stove produced. In numerous houses the authorities who provide the gas stoves on hire do not take the trouble to provide a waste pipe for the fumes, nor do they take much care in selecting the proper position for the gas stove. After wiring my electric cooker myself on a Saturday I got a sister-in-law, who had never seen one before, to do the cooking. I switched on all the elements on Sunday morning to make sure that they were all right, and instructed her how to operate the switches. The dinner was cooked quite satisfactorily. The experience that my wife has gained of the electric oven is such that she will never willingly use any other form of cooker. The author carries the system of wiring at several points to rather an extreme. On page 291 he states that the switches on the skirting board are arranged to be operated by the foot. Does it matter how they are kicked? I am in favour of the rotary type for all heating circuits because they break circuit very reliably. Many of the tumbler switches are not satisfactory, particularly on a 3-kW load. Most electrical engineers will confirm the author's experience regarding bells. His method of water-heating is most interesting, but the heater appeared to be fixed half-way up the tank in the lantern slide exhibited. Is this correct or is there an additional one at the bottom? I have used electrical water-heating for the past 5 years. In each case the heater has been fitted to the hot-water cylinder in the bathroom, a circulator being used in the one case and an immersion heater in the other. Both have been entirely satisfactory, and the first has now been in operation about 5 years. A 2-kW immersion heater is fixed one-third of the way up the 25-gallon cylinder and has proved a great boon whether the kitchen fire with its boot boiler is in use or not. A 3-heat switch is of course included. Two baths may be obtained in rapid succession and the heater is quite sufficient alone for washing days. If the full heat is switched on when rising, the water will be sufficiently hot to enable operations to be commenced immediately after breakfast. The provision of dual control from the kitchen as well as from the bathroom would be an advantage. This system of water-heating is a particular boon during the summer months, when it also assists the supply undertaking. The heater may also be put on the low-heat elements in series throughout the night, thus increasing the life of the elements. I note that the author uses 15 gallons of hot water per person per day; this seems rather an excessive amount. The costs for radiation heating seem to be rather low, but the cooking costs are somewhat higher than I am experiencing for a household of six. In Leeds the tariff of 15 per cent of the rateable value, plus ½d. per unit, is a great advantage, and whilst I have not installed meters on all the circuits, space being much too valuable, I am fairly confident that the cooking does not cost us more than 1d. per person per day. We have two enclosed boiling rings but should prefer one open and one closed. When properly used the enclosed ones are much more economical and for numerous services, such as cooking potatoes, etc., the heat may be switched

off directly the water boils. Much, of course, depends on the actual person operating the cooker. Anything that will ease the burden of cooking should be strongly advocated and helped forward by all authorities. In the reports of many medical officers of health, including that for this city, much of the ill-health and sickness is attributed to the low standard of feeding, largely due to the use of pre-cooked food, tinned food, etc. The more universal adoption of electric cooking should reduce this considerably, with very beneficial results. By the omission of fireplaces a considerable amount of space in the room is saved and the rooms are made much more convenient for fitting carpets. The corners of the room on the same side as the fireplace will also be much warmer than they usually are with the ordinary open fireplace. I fully agree with the author on the question of the radiant type of heater. Personal experience has demonstrated this very effectively. The type of heater which is provided with a reflector has a greatly increased efficiency, but some makers have entirely missed the point by placing the reflector to reflect the glow of a lamp with a little imitation coal filling, the actual heater being placed quite away from the reflector.

Mr. H. Moss: As a contractor I am particularly struck with the question of the wiring of the author's house. The whole installation is controlled, I understand, by a 50-ampere switch. On that the author has something like 36 or 37 15-ampere circuits. It would be interesting to know what is his maximum load at any particular time, because I feel that the main switch is somewhat on the small side. Although he uses large conductors in many instances, in others he appears to have economized unduly. In Bradford a 3/·036 cable is loaded to carry 7 amperes, not more. I gather from the paper that the author is loading his 3/·036 cables much more heavily. If that is so, he has overloaded his cables with his heating circuits. Another remarkable thing about his wiring is that if he puts only 3 or 4 lights in, he uses the same size of conductor for ½ ampere as he does for his radiator circuits. Has he any reason for using the one size to carry two such different currents, one possibly 10–13 times as great as the other? Not many people would incur the expense of a tough-rubber cable for their bell circuits, although this would undoubtedly make the best job. In my opinion, the switching is somewhat overdone in having lights controlled from 7 points, as it must be rather costly. With regard to the question of plugs, I quite agree with the author that it is a great advantage to have a fair number of heating points or lighting points by means of plugs in the rooms, but some would think that he has rather too many. I was rather surprised that the author had put in a wash boiler instead of a washing machine. The former takes an hour to wash the clothes, whereas an electric washing machine would do the same work in 10 minutes. I am somewhat doubtful about his drying closet. If he lives in a dusty area, in a dry period I think that the fan will draw in a tremendous amount of dust. It would be of great interest if the author would state what ratio the electrical installation bore to the total cost of the all-electric house. We are quite aware that builders, housewives, architects, and everybody concerned with the matter have a bad habit of cutting down the installation costs to the lowest possible level. In this case the author apparently has spent money quite freely, and it is hoped that he will reap a great reward from it. The success of "all-electric" houses will no doubt depend in the future on the rates at which we can buy current, and as these rates vary in different towns in the country it is very difficult to make a comparison. Sometimes it is difficult to make the ordinary householder understand what these rates are, and I should like to see a flat rate for all domestic purposes.

Mr. G. Mott: The author has told us that he spends something like £41 per year in electric lighting, heating, cooking, and so on. I take it that with the capital charges this amounts to about £1 a week. He is buying the day load at 0·5d. per unit, and his night load at 0·375d. per unit. I happen to be Chairman of a Gas Committee, but at the same time I am not absolutely opposed to electricity; rather, I may say I am progressive. At the same time I have learned a good deal about the usages of electricity from the paper and the discussion, and I can quite see that, from the author's point of view, electricity is the only means of lighting or heating a house. At the same time it must be remembered that at the present time the smaller type of houses is inhabited by people who are not in the author's favourable position. They may be called upon to pay 14s. or 15s. a week in rent and rates, and they cannot afford to pay more than a very small proportion of the costs given in the paper. What can these people conveniently afford to pay with an ordinary wage of £3 10s. or £3 5s. a week? What can they get in the way of electricity? In Ilkley the rates are fairly high, viz. 8d. per unit for lighting, 2½d. for power, and 1d. for cooking. The ordinary working man cannot afford to install electricity at these rates. Otherwise I think that the scheme is an excellent one. After all, as has been said before, health comes first, but we cannot all afford to go as far as the author has done to this end.

Mr. A. F. Carter: As the owner of an all-electric house for nearly 2 years I am in a position to corroborate the author's figures. The house contains 8 rooms and the annual consumption is just under 10 000 units. Under the local tariff this works out at 0·56d. per unit. One of the difficulties of the conversion of an existing house is the capital cost, and I think that much more could be done by the supply undertakings in providing facilities for the hire-purchase of the complete electrical system. Some two years ago I tried to borrow money from a building society for the purpose of building an all-electric house, but they refused to lend unless flues and fireplaces were put in, as they considered that the electric house would be a failure. My experience with 10–15 ampere interlocked 3-pin switch-plugs has been unfortunate, mainly due to flimsy construction and lack of breaking capacity where one pin is earthed. Flexible cables also are difficult to obtain in the 3-core heavy-capacity sizes and are not altogether satisfactory when obtained. The question of lamp renewals is a fairly serious one, and in future I think I shall adopt the author's plan of underrunning. The cost of energy for water-heating at 0·5d. per unit is not excessive,

but it does not encourage the user to give a 100 per cent load factor, which he could easily do. I think it would pay undertakings to supply, say, 500 watts of energy continuously day and night at a figure of, say, 35s. per quarter; this works out at about 0·4d. per unit. Three hot-plates are desirable on any cooker, one of which should preferably be of the enclosed type having a fairly small loading for simmering purposes. A large amount of trouble now experienced with open rings would be avoided if an instantaneous circuit breaker were installed at the source of supply. The breaker can be set at 75 amperes and still trip out and clear the cooker open hot-plate circuit—when a short-circuit takes place due to the boiling over of a saucepan —before the 10-ampere fuse will blow. In fact the tripping is so quick that invariably the element is uninjured and the slight delay in putting in the breaker allows the short-circuit to dry out owing to the stored heat in the hot-plate. In fact I think that the day is not far off when supply undertakings will install in private houses a padlocked instantaneous circuit-breaker set to trip at, say, 10 kW and give a supply for domestic purposes at a fixed figure per annum based on some form of tariff such as the rateable-value system.

Mr. C. N. Hefford: With regard to the heating of water, I do not agree that ½d. a unit is too much, especially in the smaller and medium-size house where the quantity of hot water that will be required will be less than that provided for in the author's scheme. One thing, I think, which we must bear in mind with regard to these electrical houses is that we are trying to put into the hands of the public a very simple machine. We do not improve matters if we are going to arrange it so that the occupiers have to consider when they will switch the heat on for the water, and arrangements have to be made for somebody in the house to switch it off on rising in the morning. I wish to emphasize that point, because electricity here is very cheap and I cannot understand why electrical engineers should go out of their way at every opportunity to make the general public think that it is dear and that it must be used sparingly. Another point is the provision of separate utensils. Here again we have to place something simple in the hands of the housewife. She wants something to-day to resemble a gas cooker as closely as possible. The early electric cooker involved too much thought. People who are busy with cooking and domestic work generally do not want to think; they want to do things almost automatically. The author has, I think, brought out that point rather well when he says that, after all, the working of the house will be judged more from the point of view of comfort and ease of working than the cost, and this affects the question of separate utensils with their plugs and unwieldy lengths of flexible cord. A stove is needed which will give heat and on which any of the usual utensils can be put, possibly somewhat modified but of the usual shape. We are sometimes told by people that they like electric cookers very much, but that they cannot see any flame. That shows the temperament of the people who are using these appliances. They are not yet sufficiently educated to use properly the cooking utensils which I think have been rather suggested by the paper. Then again there is the question of portable radiators in a bedroom. I am not in favour of them. If one is in the fireplace, or whatever takes the place of the fireplace, it occupies a certain place to which one is accustomed. It is quite easy to have the armchair by the radiator. The maximum of comfort is reached by having a switch near the bed, so that the fire can be switched off when not required. The separate charge for night energy is likely to introduce complications. In most towns at night newspapers are published, ice factories are run, and possibly continuous chemical processes. How can any concession be made to people who switch on and off at a certain time, unless it can be extended to the other people who are using it during the same hours and produce an equally good result so far as the power station is concerned? I agree with the author that electric houses will eventually have to be specially designed. We are suffering to-day of course from the necessity of having to adopt a type of house which is specially designed for something quite different from electricity. That condition imposes a very great handicap, but I am not sure it is not justifiably asked for. We do not find many men who will build a house primarily designed to use electricity and nothing else, as the author has done. The burning of refuse is a very real difficulty. It is one we should like to gloss over. The Medical Officers of Health are taking up a very strong attitude on this point to-day. We have to provide some efficient means of burning certain classes of rubbish within a few hours of it being formed. A number of electric houses, I hope, are to be built in Leeds. It is almost entirely on that account that we have arranged to provide in those houses one open coal grate in which rubbish of that character can be immediately destroyed. Failing that, I think there is nothing else to do at present but provide a coke fire of a certain type, thus introducing a complication which the housewife would not appreciate. We have to get rid of our rubbish. Until the sanitary authorities are prepared for more collection, and provide a different type of bin, that difficulty can only be met by some form of fire. A previous speaker mentioned that in the artisan class of house there is only one fireplace and suggested that we are not going to do much in the direction of providing a smokeless house if we leave them one fireplace. Surely that is not so, because the great amount of smoke from the chimney of that house is produced mainly by cooking and the heating of water in the boiler behind the fire. If the occupier is going to use that fire, at any rate during the summer months, only on such occasions as he has to get rid of a little rubbish it will possibly be for a matter of only two or three hours. We have had to do it in my own house—it is the only way of getting rid of certain rubbish during the summer. The draught behind the hot-water boiler in the kitchen grate is sufficiently keen to burn it. The smoke from the artisan's house will be very much reduced even if we leave him his one fire, by providing him with electrical appliances for heating the bedrooms and heating his water, when his fire is not available, and also for cooking. The schedules of cost on page 297 are particularly interesting to me. If we take a

house in Leeds having an assessment of £50 a year, and assume an annual consumption of 16 000 units—which I estimated some 6 months ago when attempting to arrive at a figure—the actual cost would be a few shillings less than that shown in Table 3. The author's house is, I think, somewhat larger, but how many people live in it ? Can the author give us any information as to the size of the vertical flue or ventilator, and also the size of the inlet and the outlet of the room ? Are they adjustable ?

Miss M. M. Hancock : I am particularly interested in the paper and this discussion, as I am just arranging for an all-electric house. It is a subsidy house and there is no convenience for a drying closet, and I am afraid I cannot afford any room for the purpose. The drying will have to be done in the kitchen. Would the author recommend a radiator or a fan or a combination of the two ? Has he found any particular medium more suitable than another for blacking underneath the cooking utensils ? I am trying to run the house without a maid and be at business in the day time. I started off originally with the idea of a slow-combustion stove, some sort of coke-boiler. I tried to find some form of coke-boiler that would keep alight all day and night and that would be labour-saving in every way. I found that instead of saving labour I should be adding to it. I found that if I used coal it would clinker, and that if I used coke I should get the fumes, and if I was not very careful the draughts would put the fire out during the day time when I was out, and that in any case I should have to clean the stove out every day. There was another consideration ; I found that I should have to keep a second supply of anthracite coal or coke, and also keep coal for my ordinary fireplace. On account of space in subsidy houses the coal store will barely accommodate a ton of coal as a rule, and to divide that into two would mean that I should have to have somebody in the house very frequently to take in a load of coal. After visiting the Liverpool all-electric house in August I decided that it would pay me to have an all-electric house because, like the author, I am quite willing to pay for convenience. In Wakefield, where I live, there is no flat rate. It is only by special application to the Corporation that I am on an experimental basis, and they estimate that I shall use about 6 000 units per annum if I have a friend to share the house. That will cost, on their rating, approximately £26.

Mr. H. J. Hodsman : If any doubts as to the theoretical possibility of the all-electric house previously existed they have now been removed, but is it desirable that the all-electric house should be encouraged as a domestic institution on a civic or national scale ? I have in mind the problem of supplying the needs of the 120 000 or so houses in Leeds. Look at it first from the consumer's point of view. While recognizing the advantages of cooking by electricity the disadvantages must not be overlooked. In this connection I should like to draw attention to the need for continuity of supply. Almost every Sunday my supply of electricity fails between 12 and 1 p.m., a very important time in the household. Turning to domestic heating, I am glad to notice that much has been made of the necessity of adequate ventilation, which too often is overlooked, but I would invite a more quantitative examination. On approaching this subject one ought first to study the work of the physiologist on the hygiene of heating. Much has been done on this problem, especially by Prof. L. Hill of the Medical Research Council, whose conclusions show a marked leaning to open-flued fires so far as British conditions are concerned, in that they combine heating by radiation with adequate ventilation. The coal fire would meet the physiologist's point of view very well in this particular, but it has the disadvantage of causing labour and producing smoke and dirt. Strange as it may seem, Prof. Hill's conclusions are favourable to the normal type of gas fire, as being on the whole the best available solution of the problem. It is true that electrical heat if used freely enough can be made to supply the aeromotive force to cause a ventilation equal to that of a gas or coal fire. If it is desired to ventilate in this way, however, it will be necessary to supply electricity at a figure in the region of 0·3d. per unit (and below in some districts) to provide the consumer with a combined heating and ventilating service equal to that obtainable by the use of a modern gas fire. So far as heating water is concerned, the problem is most severe for the electrician. I supply my own needs by means of a coke-boiler and I am quite satisfied that this gives me much better value for money, considering not only the hot water but other attendant conveniences; for instance, the disposal of kitchen refuse, a very important matter, as Mr. Hefford has so far recognized as to concede the necessity for one solid-fuel fire in his scheme of all-electric houses in Leeds. The coke-boiler solves this problem and at the same time provides an adequate supply of hot water. This, I think, is a substantial advantage from the point of view of public health. The general question I wish to raise is: Is it right so to deprive the general householder, especially when of small means, of the opportunity of getting better value for his money by limiting him to the use of electricity ? I think it will be agreed that the all-electric house will not become general in the sense outlined at the beginning. Thus Mr. Hefford himself finds it necessary to install one coal fire in his scheme of all-electric houses. That being so, how is the smokeless city to be attained ? One is thus driven back to fuel heating, and if this is to be smokeless we must employ our carbonization industries more extensively. Other considerations, such as the supply of liquid fuels and other necessities of civilized life, add further weight to this conclusion. Now the carbonization industries differ from the electrical industry in obtaining a number of products, chief of which is the gas. If we are to obtain carbonized fuel at a reasonable price, this gas must secure a market, and the market where it can be used most effectively and to the best financial advantage is the domestic market. What applies to the gas industry applies with equal if not more force to the metallurgical coke industry, which seeks ever more clamantly to find in the town's gas industry a sale for the gas necessarily produced. By this means it is hoped to cheapen the coke so essential to the iron and steel and to the engineering trades of the country. Indeed, it was recently stated that cheaper coke is vital to the iron and steel trades. I submit that, viewed from the standpoint of national

well-being, no good purpose will be served by any interference with the natural development of the industries of carbonization, be they the existing high-temperature industries or any low-temperature industry that might be established in the future. I suggest, therefore, that electricity should not be applied to purposes for which it is not naturally fitted and that the possible repercussion on the general industry of the country should be considered. I believe that some electrical engineers expect that the general adoption of domestic electrification would benefit the supply industry, and perhaps cheapen electricity. In America, which is supposed to be a pattern as regards the generation and supply of electricity, it is quite common for a public utility company to operate the supply of both gas and electricity in one city. They continue, nevertheless, to build new gasworks and extend old ones. I do not propose to explain this, but I suspect that they find, in a country liable to great variations of temperature, that the domestic load might become a nuisance if pushed to extremes, and that it is preferable to cope with much of it by means of the gas supply. I have recently been discussing the same point with the official responsible for the public gas and electricity supply of the city of Munich, who was engaged upon a tour prior to extensions of the Munich city gasworks. Munich is supplied from hydro-electric stations in the Bavarian Highlands, and yet the cost of electricity in general there, so far as I could gather, is not materially less than in Leeds. For domestic purposes, however, the charge in Leeds seems to be the more favourable to the consumer. The tariffs in Munich are evidently not drawn to favour the domestic consumer and, as already mentioned, an extension of the gas supply is in preparation. The electricity supply industry is based largely upon the use of low-grade small fuel obtained at much below the average cost of production of coal. This is only possible because the domestic consumer pays so much more than the average. Now, if the all-electric house became national the house-coal consumer would be abolished and therewith the subsidy which he pays to-day to the electrical industry. The power station would have to pay the average cost of production of the coal used, and presumably that cost would have to be met by increased charges. That again is a reason for asking whether the all-electric house would be so helpful to the electricity consumer in general. The author seems to brush aside such questions as irrelevant because the normal consumer does not inquire about coal conservation, thermal efficiency, and economic questions. Is this an attitude to be endorsed? As technical men it is our duty to examine technical problems from every point of view, so that our considered decisions may furnish sound guidance to those responsible for public funds—national or local—and to those faced with important decisions concerning housing problems.

Mr. D. M. Buist (*communicated*): The author has certainly proved the all-electric case for the 10-roomed house, but supply engineers, as a body, are more concerned with the 4- or 5-roomed house, as it is from this type of house that about 90 per cent of the domestic load will come. To make this size of all-electric house pay both supplier and consumer, the initial and running costs will have to be much lower than they are at present. This means: (1) That only such essential apparatus as cooker, fires and water heater can be installed; (2) that the initial cost of such apparatus must be wholly, or partly, paid by the savings effected by the architect in elimination of chimney breasts and the coal cellar; and (3) that the tariff must be a minimum. So much has been written of late upon this subject, and so many different opinions have been expressed regarding the various details of it, that one cannot see the wood for the trees. From the fact that about two undertakings per week are now extensively taking up the domestic heating and cooking load, one must not assume that instant success will be achieved by such undertakings, and that all that has to be done is simply to connect up and let the revenue pour in. The subject, in its details, is peculiar to each undertaking, and consequently I consider that, instead of following others blindly, each undertaking should first equip a number of houses experimentally, as some towns are doing, and thus feel the pulse of the local public upon the subject, and also at the same time enable the supply engineer to ascertain for himself which makes of apparatus are, in his opinion, the best. Glasgow, a pioneer in the matter, adopted this experimental course and, although *all* that they have done cannot be universally followed by other undertakings, their experiences have afforded many lessons. Glasgow, in common with other cities, has proved the necessity for retaining one coal fire, with boiler attached, in the living-room of 4- or 5-roomed houses, chiefly in order to obtain an adequate hot-water supply, and also to heat economically the one room which is used more than the others in such houses, and lastly (and by no means least important) because the "romance of the coal fire" has a very strong influence with the public, rather than with the engineers who, after all, are only required to supply the public with what it demands. The three objections to the all-electric house, enumerated by the author on page 289, are of greater importance in 4- or 5-roomed houses than in 10-roomed houses. Other equally important difficulties in the smaller houses are: (1) Clothes washing and drying; (2) the provision of a cooker as safe, as speedy and as simple as the gas cooker, and also one which requires as little intelligence to use; and (3) the provision of ample hot water at all times and for all purposes. It is a far cry to the day when the artisan with a family of three or four and an income of £3 to £4 per week will be able to afford to adopt electricity for all purposes, but progress in that direction is sure although, at present, inevitably slow.

Mr. R. A. Thwaites (*communicated*): Looking at the problem of the terms of supply to an all-electric house from the point of view of a sales engineer, I venture to think that if the all-electric house becomes established on a large scale the tariffs such as offered by Glasgow and Leeds will prove unremunerative, and either the fixed charge or the unit rate will have to be increased. One speaker using the Leeds Corporation's supply has mentioned that his average cost for 10 000 units worked out at 0·56d. per unit. I find that a power

user in Leeds having an annual consumption of 2½ million units per annum is required to pay 0·66d. per unit, and it is difficult to justify supplying the domestic consumer at such a highly preferential rate. I understand that the Glasgow Corporation, however, make it a condition that the average price shall not fall below ¾d. per unit. So long as the number of all-electric houses is few, this aspect of the question is relatively unimportant, but let us assume Glasgow with 20 000 all-electric houses, each with an average consumption of 10 000 units per annum. We then have an annual consumption of 200 000 000 units (an amount greater than the present total sales of energy in Glasgow). If the average rateable value is even as high as £80 per annum the average price on the present tariff would be 0·75d. per unit, compared with which the average price obtained by the Glasgow Corporation for the year ending May 1925 was 1·64d. per unit. In other words, the occupier of an all-electric house would be paying less than half the average price paid by other consumers (including large power consumers). This might be justified if the whole of such domestic load were off-peak, but such is not the case, and taken to the limit the domestic load might even create a peak of its own and necessitate offering power for motors at low rates in order to fill up the new valleys. Whilst admitting that I am enjoying the benefits of a similar tariff in Leeds, I feel that it behoves those of us who have a hand in the framing of tariffs to look ahead and see if we are not tending to cut the prices for domestic load too much. With the author's remarks concerning cookers in general, and hot-plates in particular, I am in entire agreement. From figures collected it would appear that the consumption for cooking is about 4½ units per day for the cooker, and ½ unit for each person. The drying cupboard is an interesting feature, and it would be of interest if the author would, in his reply, give a sketch showing the detailed arrangement of this. The author was very wise to provide so many plugs; my own regret is that I installed too few. He suggests that an all-electric house often saves one maid-servant, and my wife assures me that in our own case this certainly is so. As the total cost of a maid is not less than £80 per annum, this is a very strong point in favour of the scheme and is usually overlooked.

[The author's reply to this discussion will be found on page 328.]

North-Western Centre, at Manchester, 15 December, 1925.

Mr. S. J. Watson: The author suggests the possibility of electric cooking being transferred from the kitchen to the dining-room, but I think it is essential to cook food as far as possible from the place where it is to be eaten. The most important point in connection with the all-electric house is the provision of hot water. I have no hesitation in saying that upwards of 90 per cent of the fuel burnt in an ordinary domestic house is used solely for the purpose of providing a hot-water supply. In Salford we are building at the power station, to accommodate some of the key men, four houses which we call all-electric, although this term is not quite correct. No provision is being made for a coal fire in the bedrooms or sitting-rooms. We have had the courage of our conviction that the coal fire is not necessary and therefore we are not providing concrete round the chimney breast or a chimney breast itself, and I am given to understand that we save somewhere about £15 a room—that is the cost of the fireplace, the preparation for it and the proportion for chimneys. The only fireplace we are putting in those houses is one, in a sort of kitchen sitting-room, with a boiler at the back, so that the fire will not only warm the room but also—I think this is a point of some importance—burn the debris which accumulates in a house. In the strictly all-electric house described by the author no arrangements are provided for dealing with debris, but I think it is essentially a matter to which attention should be given. The boiler will be connected to a cistern in the usual way, but we realize that there may be times when the fire will not be wanted and therefore it is proposed to put immersion heaters in the tank so that, whether there is a fire or not, hot water may be obtained for washing-up or for baths. Where there is a young family a more ample supply of hot water is required than is generally thought necessary. In these houses a washing boiler and cooking stove will be provided, together with radiators in the best rooms and another which can be used in any of the upper rooms in their turn. The houses will therefore be entirely electric apart from the one fire I have mentioned. The author refers to a two-part tariff. Those of us who are engaged in the electricity supply industry will entirely endorse this remark that if any progress at all is going to be made in the use of the supply for domestic purposes it is absolutely essential that a two-part tariff should be applied and the tariff consisting of a charge based upon the rateable value, plus a very low charge for each unit consumed, is one of the best in vogue. The undertaking with which I am associated has adopted a tariff of 12 per cent, plus a running charge of ¾d. per unit. It may not be without interest to mention how we arrived at the secondary charge of ¾d. per unit. At the works we have a canteen and when I went there some three years ago I found that all the cooking was done electrically. As no figures were available showing a comparison with gas, I arranged for a gas stove to be put in and since that time we have cooked one week by gas and one week by electricity. The result has shown absolutely conclusively that electricity at ¾d. per unit for cooking purposes is comparable with gas at 3s. 6d. per 1 000 cub. ft. The author exhibited a lantern slide showing a load curve for August, but in that month very little heating is required. I suggest that he should have supplemented that curve with one for about the middle of December when the weather is cold and a larger quantity of heating is required. He also remarked that the domestic load would not make much, if any, difference to the maximum demand, but I am afraid I cannot accept that suggestion because

it naturally follows that if a large number of domestic appliances for heating, hot water, etc., are connected they will add to the total load. Cooking is the only domestic supply on which any considerable diversity occurs. On a cold day all the radiators will be on and this will add to the load on the station. It is unfortunate that no very definite figures are yet obtainable in regard to the diversity of the cooking load. I have seen figures put forward showing it to be as high as 10, and others showing it to be as low as 3 or 4. I imagine that the diversity of the cooking load is really somewhere in the region of 7. That is based on the results obtained by an undertaking which has put in a considerable number of cooking stoves during the last few years. The total cost per annum for the all-electric house shown on the lantern slides was given as £43. Bearing in mind that the cost includes the equivalent of all the coal that would be burnt as fuel, I am certain it is not exorbitant. On the other hand it is really extremely economical and a very sound proposition.

Mr. J. L. Carr: I agree with Mr. Watson that the domestic use of electricity can only develop extensively provided a suitable two-part tariff is adopted, and in that connection I should like to make one or two suggestions from personal experience. I have observed that the lighting consumption in the winter quarters is approximately double that obtaining in the summer quarters, and it is interesting to see from Fig. 7 that the total consumption for an all-electric house is in approximately the same proportion. In this district the standing portion of the domestic charge is divided into four equal parts. As one who has some knowledge of the subject I can appreciate that, taken over the 12 months, this has no influence on the average charge, but for the benefit of the lay man it would be a distinct convenience if the standing charge were arranged differently, say one-third of the total annual charge for each of the winter quarters and one-sixth for each of the two summer quarters. By doing this the consumer's bills would be strictly comparable with those previously obtained by running on a fixed cost per kWh. Although it may seem of little importance to some engineers, it would be a distinct convenience to the average consumer for the purpose of comparing costs year by year. Mr. Watson informs me that that method is now adopted in Salford. There are several points in connection with the installation which call for comment. I was surprised to see that in place of what we consider to be the best practice in the wiring of a new house—that is, solid-drawn heavy-gauge steel conduit—the author has adopted the hard-rubber-sheathed cable. In the case of the conversion of an existing house for domestic use there is some excuse, and possibly very good reason, for using one of the various systems of surface wiring at present on the market, but in the case of a new house, where the cost of erection is a negligible portion of the total cost, most engineers will agree that the sounder job is one in which heavy-gauge conduit is used. I appreciate the author's point with regard to the number of wires concerned, but if a suitable conduit is used I do not think that should be a very serious consideration. The grouping of distribution boards will not appeal to many installation engineers as being altogether satisfactory; probably a much sounder job would have resulted by installing a section board to which each sub-section or distribution board would be in turn connected, thus localizing interruption in supply in the event of serious faults occurring on any part of the system. The question of the number of points in a room is referred to by the author. It is my experience that with a limited number of plug points in one room a certain amount of inconvenience is experienced, because it happens that after one or two plugs have been installed the furniture is removed to another part of the room, and some of the plug points are covered up and are not available for use. The diversity of the load in different rooms is quite sufficient to enable three or four small plug points to be looped if necessary. In that connection I have found it very useful to install one or two 15–20 ampere plugs in each room, and a larger number of 10-ampere plug points to allow of the use of small portable appliances such as small radiators or portable lamps. The author mentions some of the merits of electric cooking, but I think that publicity departments should confine themselves more to the recommendations that are made with regard to cleanliness, ease of operation, etc., than to making statements similar to those found in many makers' catalogues, where it is often stated that the cost of the electricity used can frequently be saved by the reduction in wastage of the meat. Those statements cannot in my opinion be justified, the saving in the meat being largely due to the smaller amount of water evaporated—not to the particular kind of heating, but to the design of the oven. The question of the reliability of hot-plates is a very important one in connection with the development of the cooking load, and in going over some records for the past few months I have been agreeably surprised to find that by the use of a protected type of hot-plate the total percentage of hot-plate failures has been considerably reduced below that anticipated. That raises another point mentioned by the author, i.e. in connection with the radiant heat from hot-plates and the effect of blacking the bottom of utensils. With the protected type of hot-plate the proportion of radiant heat is comparatively smaller than would be expected in a purely open type of hot-plate, and the benefit to be obtained by blacking the bottom of the pan is consequently considerably reduced. From a few rough experiments I have made I am convinced it is really not a good proposition to black the bottoms of the pans, for several reasons. First, the total amount of radiant heat developed is only a small proportion of the total input. Second, by blacking the bottom of utensils, particularly aluminium pans, such as one normally purchases when acquiring an electric cooker, one sacrifices a great deal in the clean and bright appearance of the equipment. Third, with black-bottomed pans one naturally has a distaste to placing them upon tables for ease of manipulation after cooking. The point made by the author in regard to the use of self-contained utensils is one with which I am in agreement to some extent and I find it a distinct convenience to provide a limited number of vessels with self-contained elements. In the present stage of development the average consumer cannot be expected to provide

himself with expensive appliances of this sort, particularly when they are so liable to break down. I am of the opinion that the development of the use of such appliances, whilst considerably reducing labour and inconvenience in connection with electric cooking, can only proceed if the supply undertakings, which in many instances hire out the electric cookers, will undertake to supply and maintain them for the consumer. In that connection it has to be remembered that considerable expense is incurred by the careless use to which such appliances are subjected by the average consumer. The total cost mentioned by the author struck me as being extremely low for an all-electric house, and I was somewhat astonished to find that my own figures, using gas for cooking, electricity for lighting and limited heating, and coal for general heating, were *per capita* practically similar to those given in the paper. During the past year, when the gas has been cut off altogether, they have been very little different from what they were before.

Mr. G. F. Sills: I consider that electric kettles take an unnecessarily long time to boil water. I have one which is rated at 1 000 watts, and it takes 12 minutes to boil 3 pints of water from 60° F. If kettles cannot be supplied with elements up to 2 kW, then an alternative, where an electric cooker is also available, is to supply one hot-plate of the cooker with a 2½ kW element in place of one 1½ kW. This enables the kettle to be boiled in about 7 minutes, and is the practice of at least one well-known corporation. The kettles, in addition to having fusible plugs at the bottom, should also be of the whistling type; this would prevent a good many kettles from being allowed to burn out. An interesting feature of the paper is that the bell wiring in the author's house is carried out with C.T.S. wire. The bell system in houses is usually extremely unsatisfactory. With reference to the position of plugs for radiators, etc., in houses specially built for all-electric supply and without any of the usual type of mantelpiece, I can quite see that the switches should be on the skirting board. Most of the power consumed in houses for a long time to come will be used in existing houses which have the ordinary mantelpiece, usually wood, and it would be much more convenient if the switch controlling the plug of the radiator, or the combined switch and plug for the radiator, were fitted on to the side of the mantelpiece close to the wall. The position would enable one to switch on at least one element of the radiator without bending down every time. I have found from experience that if a 230-volt iron is put on a 200-volt circuit it will not burn out and yet it will get hot enough to do ironing, provided it is not one of the smallest sizes. In connection with the supply from Manchester, after studying the Norwich system I came to the conclusion that I could get my current for cooking for nothing, because my bill for lighting and cooking on the Norwich system would be no larger than that for lighting only on the standard charge for lighting only. One of the lantern slides showed a fire which threw the heat towards the floor, and I gathered that the author did not favour this type of fire. I am not sure whether he was referring to a particular make, but I have come to the conclusion that it is much more efficient to throw the heat down, as unless the floor is warm one does not feel comfortable in the room. I have over 17 kW connected to the mains and am quite satisfied that on the basis of 20 per cent pre-war rateable value, plus ½d. a unit, one cannot go wrong in using electricity.

Mrs. H. C. Lamb: I can speak with confidence of the comfort which electricity brings into the home. I have used nothing but electric fires in the dining-room and in the bedrooms of my house for over 8 years, and have found them exceedingly satisfactory. I believe that it is only necessary to obtain the right type and size. The author says that he has a small dustbin which is emptied twice a week. Even if we could persuade the dustman to come twice a week—of which I am doubtful—would the cook be satisfied with that? She knows there is some animal refuse and vegetable refuse which must be destroyed at once, and she would not be satisfied to see it merely left in the dustbin for three days at least. If we have an all-electric house, why not have an electric furnace to burn the refuse? The electric oven and griller I have found to be entirely satisfactory, and I shall never wish to use anything else. The only objection seems to be the cost of the electricity. People think it is expensive, but that idea must be corrected. Where is the maid's sitting-room in the author's house? It seems that she has to use the same room as that occupied by the boiler, the sink, the oven and the washer. I do not think that sort of a room is quite suitable for a maid, and if the other rooms are going to be made comfortable the maid's room also must be included. It would have been better to have made a bigger scullery, where all the work would be done, and a little rest room where she might get away from her work.

Mr. A. Philip: The main drawback to electric cooking is the time taken to heat anything by means of hot-plates, but as regards their efficiency it is rather surprising to see such low values mentioned as 20 to 25 per cent. From the results of tests on a considerable number of different types of plates it appears that values below 35 per cent must be considered poor, whilst 40 per cent is an average figure for good types. One enclosed hot-plate, fitted in a light-weight stove, has the unusually high efficiency of 50 per cent. It should be noted that the method of test, which was intended to approximate to practical working conditions, gives figures which necessarily err on the low side. As regards the construction of hot-plates, the partially enclosed type appears to be best from the point of view both of efficiency and protection, whilst the open type is not at all to be recommended. High efficiency can be attained in general by the following:—(1) Reduction of the amount of metal used in the construction of both the hot-plate and the top plate of the stove; (2) reduction of clearance between the heating element and the cover plate to a minimum; and (3) if possible heat-insulation of the hot-plate from the top plate by a small air-gap. Loading and temperature are of course other factors to be considered. A partial solution of the hot-plate difficulty lies in the use of separate pans with immersion heaters, the efficiency here being from 80 to 90 per cent, but their initial cost is high

and they are probably somewhat difficult to clean. Reliability is mentioned several times in the paper, and apparently no provision has been made for emergencies in the author's house, but interruptions in supply do occur from time to time, and it does seem necessary to have some alternative, such as a small cooking stove and a few lamps, run by gas or oil, for use in emergency in an otherwise all-electric house. As regards domestic supply in general, my personal opinion is that the use of electricity should be extended and increased for all purposes other than water-heating and continuous room-heating, which are extremely wasteful from the point of view of conservation of fuel.

Mr. H. C. Lamb: The author is a consumer of an up-to-date and progressive undertaking, but it would not have cost him more for electricity if he had built his house in Manchester. The rate would have been practically the same. There is, so far as I know, no really all-electric house in Manchester, but we have many that are mainly electric, some of which have a consumption even greater than that of the author's, and at least one exceeding 20 000 units a year. One of the speakers in the London discussion said that it was all very well for the Glasgow Corporation to supply this one house at that price, but had there been a thousand such houses the department would undoubtedly have supplied them at a loss. I think the speaker was, however, mistaken. If the load curves of the thousand houses were identical, or if the supply undertaking had nothing but a domestic load to cater for, the houses certainly could not be supplied at the price given in the paper; but a varied class of load is required to give maximum economy, and it is the high diversity factor of the domestic demand which makes it possible to supply the electricity at a comparatively low price. Mr. Watson remarked that little or nothing was known with regard to the domestic diversity factor, but a great deal of reliable information has been published in the United States, and some information now being collected in Manchester will be available before long. Another very important factor in connection with the provision of a domestic supply at this price is that the demand is largely before 9 a.m., between noon and 2 p.m., and after 5 p.m. I agree with Mr. Watson in doubting the statement on page 298, which reads: "Thus the all-electric house in question has an aggregate consumption of about 30 times the lighting consumption, and this practically without increase of station plant." I am afraid that could not be true of an all-electric house, but it might conceivably be true of a house mainly electric; that is to say, a house possessing at least one coal fire for heating purposes. I have seen load curves from such houses which bear out the statement that the chief demand occurs at the time of day most convenient to the power station.

Mr. W. Eccles: In 1913 I had my own house fairly completely equipped. My enthusiasm lasted for 4 or 5 years, but latterly I have left the various appliances more or less in the hands of those who have to use them. It may be that I am still under the influence of the reaction from the original wave of enthusiasm, but it is more probable that I am really unbiased in the matter. My start, like the author's, was due to my thinking that I ought to have the courage of my convictions, and that courage was aided and abetted by the Manchester Corporation Electricity Department, who then offered an unlimited supply of 200-volt direct current at $\frac{1}{2}$d. per unit plus an annual charge of, I believe, $12\frac{1}{2}$ per cent of the rateable value of the house, which is about two-thirds the size of the author's house. In my house I have in all 16 heating points on 5 circuits, each 7/18 S.W.G. in conduit, and a cooking circuit for oven, hot cupboard, grill and four boiling-plates. For equipment I had nearly everything that showrooms of those days could show, and some things they did not stock, absorbing altogether 17 kW, but I did not in the least intend to have an all-electric house, as I did not then believe that it was economical or the easiest house to work. The energy consumed in the first year was 4 000 units, and in this connection it interested me very much when in a friend's house in Norway, where the tariff was per kW of maximum demand per annum, irrespective of the units consumed, to find that they had used some 4 800 units in a year on a maximum demand of $1\frac{1}{2}$ kW, whereas I had an actual maximum of 9 kW and a consumption of 4 000 units. In other words their load factor was 7 times greater than mine. It illustrates how very greatly tariff controls load factor. I am rather disappointed that the author should have been so revolutionary as to construct an all-electric house and dispense entirely with coal and gas. The result is that he has demonstrated that an all-electric house is a possibility at a more or less reasonable cost, but he has not helped nearly so much as he might have done to demonstrate the most economical equipment for a home which has to be worked either by the housewife or by the present-day maid-servant with the least possible effort or friction. If, however, the author never intended to install the most economical equipment, then I think he should have stated this clearly in his paper, as great injury can be done to the progress of the use of electricity in the home by claiming that it can do something which can be done better by either gas or coal. For instance, I am certain that the general heating of the house and the boiling of water in the kitchen can be done in this country, given properly designed arrangements, much more cheaply and effectively by means other than electricity. Furthermore, from the country's economic point of view, people should be encouraged to use low-grade energy, such as gas from which all by-products have been extracted, or coke, for water-heating, etc., and to conserve high-grade energy such as electricity for its proper uses. For these reasons the paper does not register an advance in general science and is of very little use to the general public. Taking next the point of view of those who have to operate such a house—and here my criticisms must involve the general design of the house as well as its equipment—I would fully endorse and underline Mrs. Lamb's remarks that the kitchen might be all right as a workroom but is no place for anyone to sit in in comfort. Such a house ought to have a small sitting-room for its staff, as otherwise it is a complete failure from the point of view of their comfort. Now look at the kitchen as a workroom and imagine the preparation and serving of a meal,

an operation which occurs at least four times per day. Those who have any experience of such things will see at once the entire lack of thought in the design and layout of this kitchen. It is necessary to pass through two doors to reach the larder; the cooker is at the maximum possible distance from the sink; the light is in the best position to make shadows where work is being done; the table, apparently not shown, looks as though it ought to be on wheels as it must be in the way anywhere, and especially with two doors opening inwards into the kitchen. The cupboard accommodation, too, must be scarce. I would say that the space used by this layout, i.e. 18 ft. by 12 ft., if used properly and thoughtfully would provide all that is necessary, allow for a small sitting-room for the maids, and reduce the work by at least 30 to 50 per cent. A larder of 20 cub. ft. capacity is ample to store all the perishable food that is likely to be kept in stock, but I see that the one provided is 8 times this size. This is, in my opinion, a sheer waste of space and a cause of needless walking. There is no reason why the cook should have to walk more than two steps to get anything required, and the majority of her requirements should be at hand and without needing any appreciable movement. The same remarks apply to the pantry, where everything required for the dining-room—excepting only hot cooked food—should be at hand and where all dish-washing and putting-away should be done. It will be seen that the proper place for the larder is in the wall between the cooking place and the pantry and it should be accessible from either side. In the bedrooms the lighting is very ordinary and not very thoughtfully arranged. The best arrangement for getting light where it is required at the dressing-table, bed and wardrobe, is to have those articles of furniture fitted with lights and switches, and supplied from the nearest wall plug. This allows for the rearranging of the furniture to suit the most fanciful housewife, and yet ensures the light being on the spot required. One general light controlled from the doorway is of course required in each room and from the bed, if one could be sure of the location of the latter. A purely non-electrical point is that of water supply in the bedrooms; this is such a labour-saving requirement that I cannot understand why it is omitted, as it apparently is. Ceiling sockets in the dining-room are most useful for table cooking and special-occasion lighting, and the only satisfactory and reliable bell push at the dining-table is one suspended from the ceiling. Referring to the electrical layout, the first outstanding item is that no less than 31 fuses are used and yet it has to be admitted that all portable lamps, vacuum cleaner, toasters, portable fans and light apparatus generally are practically unprotected. Personally, I should have protected the main wiring by 5 or 6 fuses at most and have devised some means of protecting the apparatus separately and in such a way that in the event of a fault it would not get blown up. It is the apparatus and not the cable that requires protection. I should never recommend anyone to have important electrical fittings in the house for cooking, heating, etc., unless there were a good service of repair men available with an ample supply of spare parts to draw on. The author mentioned this point but, in my opinion, did not emphasize it sufficiently. Its absence in my case was the cause of a gas cooker finally replacing the electric cooker originally installed. If the great untapped domestic load is to be developed, supply undertakings must push the sale of current more effectively by helping in the design and layout of houses to suit and by assisting the lay man to get a properly designed installation. Manufacturers must design apparatus capable of withstanding abuse and of being easily repaired. Electrical engineers generally must study the working of their homes and produce efficient designs for their lay friends.

Mr. W. D. Watson: Is the author's hot-water cistern of the type free from divisions, allowing the incoming cold water to mix freely with the already heated water, or is it made up of compartments enabling the user to draw off a cistern full of hot water before the cold water is allowed to mix with it and so cool it down? In regard to the author's use of unprotected rubber-sheathed cable, on the score of "safety first" is it not imperative that all cables should be mechanically protected? Nails used by householders are sooner or later sure to puncture the insulation. I have calculated the cost from the heating curve in the paper and I find that in the 6 winter months about 4 600 units were used, whilst the consumption for the rest of the year was only 1 314 units. In my district current is supplied at ½d. per unit for domestic hot water and central heating thermostatically controlled, 1d. for domestic utensils, radiant fires, etc., and 4¾d. for lighting. If the author's house had a system of central electrical heating of the "linear" or "tubular" type, the cost for the winter months to keep his living-rooms and kitchen at a temperature of 57°–60° F. would have been about £9 5s., leaving the balance (amounting to £9 15s.) for boosting-up purposes in winter and also for the small summer load at a charge of 1d. per unit. I calculate a net saving of about £4 10s. per annum based on experiments I am now carrying out. A house so heated is in my judgment far more comfortable than one heated entirely by radiant fires.

Mr. G. A. Proctor: Taking the figures in the paper, the cost of a full domestic electric service for a house having a rental of £100, viz. £43 a year, is remarkably low, less than half the rental values. Taking actual figures of a more modest house of £30 a year rental, using electric light, gas for cooking and washing, and coal for heating, the cost worked out as follows: electricity £4, gas £3, coal (5 tons at 45s. a ton) £11 5s., making a total of £18 5s. 0d. Comparing those figures the author has proved that the all-electric house is a practical proposition. The all-in cost of the electric flat referred to in the paper, rental about £40, is £14 18s. plus £2 for the hire of a cooker and 2 fires. Those figures again prove that the complete electric home is a commercial proposition. As regards the entire elimination of coal fires in the home, it would be interesting to have the views of the sanitary authorities on the question of the disposal of household refuse.

Miss E. E. Wilson: Mr. Eccles said that all his apparatus seemed to need constant repairs. I am in the position of having to leave my all-electric flat all day, the household duties being carried out by a

maid, and so far none of the apparatus has had to be repaired.

Mr. A. L. Lunn: In the introduction to the paper, the author mentions the adverse criticism received from electrical engineers when the scheme for his "all-electric" house was discussed. I have much in common with him on this point, as just over 2 years ago, when deciding to adopt electric heating and cooking, several of my engineering friends hinted that I should rue it. As one who is partly responsible for a supply of electricity, I considered that I was doing a disservice to our industry unless I was prepared to use our own products; therefore I went ahead with my scheme and now, after 2 years, I am more than satisfied with the venture. My own case may be somewhat unique, as all our cooking and the baking of bread, cakes, pastry, etc., is done in the home. The house contains 7 rooms, 2 on the ground floor, and kitchen, 3 bedrooms on the first floor, and 1 large attic bedroom. Previously, electricity was only used for lighting, ironing and vacuum cleaning, all cooking being done by gas and heating by coal fires. During the past 2 years all cooking and heating have been done by electricity, with the exception that a coal fire is used in the kitchen for heating water. When deciding upon this scheme I naturally expected that it would cost more than the previous arrangement for improved conveniences, etc.; I therefore kept records for comparison. After what I have heard during the discussion in regard to water-heating, I intend to adopt this too as soon as possible. In Manchester we are fortunate in having a very low tariff—a fixed charge of 20 per cent on the pre-war rateable value of the house, plus 0·5d. per unit—and my average cost for the 12 months ended December 1924, including the fixed charge (which is £4 13s. per annum) for 6 495 units, works out at the low figure of 0·673d. per unit. I estimate that I shall have consumed 7 078 units during this last 12 months, and the average cost for this, including the fixed charge of £4 13s. per annum, is 0·657d. per unit. Comparing my previous year's working, that is, using gas for cooking, coal fires for heating, and electricity for lighting, ironing and vacuum cleaning, the total cost per annum was £24 18s. 4d. For the first 12 months, using no gas, and coal only in the kitchen, the semi-electric house cost £26 15s. 2d., made up as follows:—

	£	s.	d.
Fixed charge	4	13	0
Cooker hire	3	0	0
6 495 units at ½d. per unit	13	10	8
Coal	5	11	6
	£26	15	2

This shows an increase of £1 16s. 10d. For that amount we have a radiator available in every room, including the bathroom and hall. I do not think it is necessary for me to mention the advantages of having radiators in the bedrooms, particularly during the very cold weather; and, apart from this, what we have saved in cleaning alone is well worth £1 16s. 10d. per annum. This last year has shown an improvement over the previous one, the total cost for the semi-electric house being £25 4s. 9d. Comparing this with 2 years ago, the increased cost is now only 6s. 5d. and, considering what we have had for that increase, it is well worth it. In col. 2 on page 291 the author mentions the use of a standard lamp on a circuit fused for 15 amperes. It is not advisable to put some of the small apparatus on a 15-ampere circuit. If ladies are using electric irons or vacuum cleaners, and a short-circuit were to develop on the flexible cable, they would be startled and lose confidence in using these appliances. It is preferable to have an intermediate plug box with a small fuse in circuit (as light as possible) between the appliance and the radiator plug. The gas was cut off at my house 18 months ago, and since then we have been dependent on the electricity supply. For over 2 years we have not had a coal fire in any room in the house, except in the kitchen. I have proved this scheme to be quite satisfactory, and if more engineers would have confidence in their own industry the electrical appliances would be improved by their experience and our smoke problem would be partly solved.

The Author's Reply to the Discussions at London, Birmingham, Leeds, and Manchester.

Prof. S. Parker Smith (*in reply*): There are, in all, 10 discussions to be replied to, and I am desirous of dealing with all points as far as possible. In order to lighten the task of the reader, repetitions will be avoided wherever possible. For this purpose a few general questions will be dealt with collectively, and later the remaining points raised by the several speakers.

At the outset I should like to make a general acknowledgment of my indebtedness to all who have contributed to the discussion. The information contained in these contributions is in many ways not only supplementary to, but of greater value than, that given in the paper. Had such information been available 3 or 4 years ago, my task in designing the electrical equipment of my house would have been incomparably easier.

In response to requests, it is hoped that a curve similar to that in Fig. 8, but taken for a winter's day, will appear in my reply to one of the later discussions.

A few points will now be dealt with collectively.

Waste of national resources.—No member of the Institution needs to be told that electrical energy obtained from a coal-fired station working at about 20 per cent efficiency is not the most efficient method of obtaining heat for domestic purposes. Nevertheless, one speaker after another has supplied figures which prove that, with the tariffs on which the paper is based, there is roughly no difference between my costs and those of similar houses using gas, coal and electricity. At the same time the many savings obtainable with the use of electricity are admitted. How is this to be explained? Though the number of heat units brought to the house is much smaller in the case of electricity

than with coal and gas, the utilization of the former is much better. An electric fire and an immersion heater have efficiencies approaching 100 per cent, for all the convected heat from an electric fire adds to the warmth of the room, whilst the losses from a well-lagged tank are small. Also the electric oven uses heat more efficiently than the other ovens do. Again, the stand-by losses with electricity are negligible, whereas a coal fire may have to burn all day whether it is needed or not. True, many forms of heating give a warmer house than is obtained with electricity; but is this necessary? So long as the persons are warm and there is no discomfort, what complaint can be made? In addition, greater comfort results from occasional heating in bedrooms, bathrooms, etc., where electricity is available. It may be said, however, that all this evades the charge of wasting national resources, and that it is no answer to say that with electricity the waste occurs in the power station instead of in the house. Yet some weight must be given to this point. The fuel in the station costs about 15s. per ton against 40s. in the home—part of the latter represents avoidable distributive costs. Now let us see what it means when we use a coke-fired boiler for hot water. The coke has to be ordered and stored; the boiler has to be maintained, cleaned and stoked all the year round. The saving, accepting Miss Fishenden's figures, would be £5 to £9 per annum, according to circumstances. Personally, at the risk of being called extravagant, I think it is worth this sum for the comfort, convenience and reduction in labour. A home cannot be designed on the same lines as an office or a factory. We are not expected to burn coke in our grates instead of coal, though it might reduce smoke and assist certain industries. Here also we must be allowed to choose the form in which we buy our heat units. The fact that so much less labour is needed in the home without increasing the overall costs should not lead us into making a fetish of economy. Life is more than economy. What cheerless places our homes would be if economy alone ruled our lives. At the moment we can be happy that electricity with all its advantages can be obtained without increase of cost. Lastly, may not some service accrue to the community by reducing the demand for domestic servants; also is it not a national service to reduce all unnecessary distributive costs—some 10s. to 20s. per ton on coal and coke?

Extravagant installation.—Many speakers, especially contractors, have questioned what to them appears to be the lavish way in which the house has been wired. Now it must be remembered that most electrical engineers with whom the scheme was originally discussed condemned it outright; also that financially it was a very serious venture for me. Critics must not be surprised therefore that I was prepared to take no risks. As a designer I knew many of the pitfalls, such as cheap material and shoddy work, and I determined to give the scheme every chance. The latest edition of the Institution Wiring Rules proved a sound guide and every effort was taken to do the work as it should be done. As regards the switching of the lighting circuits, I am convinced that the enhanced convenience is well worth the small extra cost. The fusing of the power circuits is not so easy to settle. Ought the simplicity and convenience of interchangeability to be readily sacrificed; and is a 5-ampere fuse a much greater protection for an appliance taking, say, 100 watts, than a 15-ampere fuse? There may well be room for differences of opinion on such points.

Capital cost of installation and appliances.—It is hard to see why members of this Institution should require this information to be given in the paper. Full details of the layout are given and costing of any desired part is a simple matter for any electrical engineer. Each case must be worked out according to requirements. The paper is intended to give details of running costs for the several services, for it is here that a degree of uncertainty has prevailed hitherto.

Smoke abatement.—The amount of sunshine in these islands is all too little, especially in winter; and of the small quantity available it is claimed that city smoke—four-fifths of which is produced by domestic chimneys—robs us of about half its healing (ultra-violet) rays. Is it too much, therefore, to regard preference for the coal fire as being somewhat selfish? Who knows whether the present movements will not compel us to provide cleaner homes in healthier surroundings for our people? Should not altruistic thoughts of this kind make us very cautious in advocating the retention of one coal fire?

The last coal fire.—Many speakers advocate the retention of one coal fire—some for romantic reasons, others for obtaining a supply of hot water, others for burning refuse, and yet others for occasional use. The domestic labour problem seems to be dealing pretty effectively with the romantic side. The use of a coal fire for obtaining hot water is not so easily disposed of, especially in districts where the charges for electricity are on the high side. In such cases it may be better to fit an immersion heater in the hot-water tank for use in summer and to lag this tank to reduce losses. Also, for occasional heating in spring and autumn, the electric fire becomes a logical adjunct of high tariffs. In my opinion, however, it is desirable to go the whole way where tariffs make this possible, for in such cases experience tends to show that the cost of electricity alone is less than that of electricity and coal. Certainly the retention of a coal fire in the kitchen alongside an electric cooker may cause complaint on account of cost. The disposal of refuse appears to be a thorny problem. Some speakers agree with me that removal of refuse is paid for in the rates and ought to be properly done by the local authority. A larger number, however, are horrified at the idea of allowing garbage to accumulate for, say, a week. The personal equation is evidently important in this connection. As a result of inquiries I am inclined to believe that the facts are not always correctly understood. Many people imagine that their refuse is burnt on the premises, when actually it is thrown into the bin. In artisan classes refuse is often burned on account of its fuel value. In a house with one coal fire (and that fire in the sitting-room) the burning of refuse must be very objectionable. It must be remembered that in an all-electric house the total quantity of refuse is less than in a house where coal is used. Should, however, the householder insist on burning his own garbage, I should suggest than an

incinerator is preferable to a coal fire. The smoke question alone would justify this opinion. To light a fire daily in summer to dispose of refuse would entail too much cost and trouble for most people. In some countries, nuisances from garbage—arising from smell or mosquitoes—are prevented by depositing the garbage in old newspapers, which can be twisted up before being thrown into the refuse bin.

Tariffs.—It has been clearly proved that the success of the all-electric scheme is dependent upon suitable tariffs. It should, however, be particularly noted that the tariffs existing in Glasgow are not unique. Many other cities such as Hastings, Liverpool, Manchester, Sheffield, Leeds, Wolverhampton, Worcester, etc., have practically the same rates for domestic consumers; though power companies are not so progressive.

Living in a cool atmosphere.—This point has been ably argued—some have urged the hygienic advantages of a comparatively cold atmosphere, whilst others find warmed air more comfortable. My experience may be peculiar, but even in the coldest weather the house has not been chilly nor has there been discomfort from cold walls. It should be mentioned that (weather permitting) in winter as in summer there is generally an open window in every living-room and bedroom. The figures given in the paper, viz. 50°–55° F., were taken, if my memory is correct, from an article of Miss Fishenden, written for a special number of a journal, as being the comfortable temperature with ample radiant heat. I confirmed these figures and used them to replace somewhat higher figures of my own.

All-electric dwellings for artisans.—It would be very disappointing to find that the all-electric idea cannot be applied to artisan dwellings with the Glasgow and similar tariffs. Fortunately, figures are given which show that the case is feasible. In Table A, Prof. Barker gives 3 180 000 B.Th.U. per person per annum as the number of heat units needed for heating, hot water and cooking in an artisan's home. Let us increase this to 3 400 000 B.Th.U. (= 1 000 units of electricity) to allow for the low efficiency of the electric cooker. Mr. Grierson found that the average annual cost in 5-roomed houses for these services was £16, or about 6s. per week. This sum would be just sufficient for a household of 5 persons each using 1 000 units per annum with energy at 0·75d. per unit. This figure of 5 000 units per annum is also confirmed by the figure of 5 350 kWh in the footnote on page 312. Moreover, these figures will be improved in future by higher cooking efficiencies. It can easily be seen that the problem is within the bounds of practical discussion. Thus where energy is offered at about ¾d. per unit overall, the workman's house ought to be seriously considered. For example, the fixed charge of a 5-apartment house in Glasgow is £5 4s. per annum; so that at ½d. per unit and an expenditure of £16 per annum, the yearly consumption would be 5 184 kWh.

Cooking utensils with self-contained elements.—It is difficult to predict at the moment whether such utensils will replace boiling-plates. My experience has proved that their use has practically halved the consumption for cooking—a saving of nearly 30 units per week. When it is remembered that such pots will be nickel-plated, mistake-proof, readily replaceable, suitable for hiring out, etc., one is almost encouraged to believe that they have a future. Moreover, a frying-pan with built-in elements, and a light oven of low heat capacity, may also serve to reduce consumption still further. It is important not to be too conservative in our ideas —let us first produce the right articles before we condemn the principle. In response to several requests, the sketch embodying my ideas is reproduced in Fig. A. The oven, pots and fry-pan are interchangeable at any of the 3-heat points. A grill and an enclosed boiling-plate for ordinary pots are also provided. The metal-top table provides the earthing device. It is intended to dispense with flexible cables and provide simple mechanical interlocks. The pins, etc., are shown exaggerated to make the ideas clear.

In reply to Col. Crompton, in theory there is no need for a fireplace. Actually in Great Britain people prefer to sit round a fire (or fireplace). At the same time, there is no reason to have only the one fire. In many cases it is better to distribute the heating, and

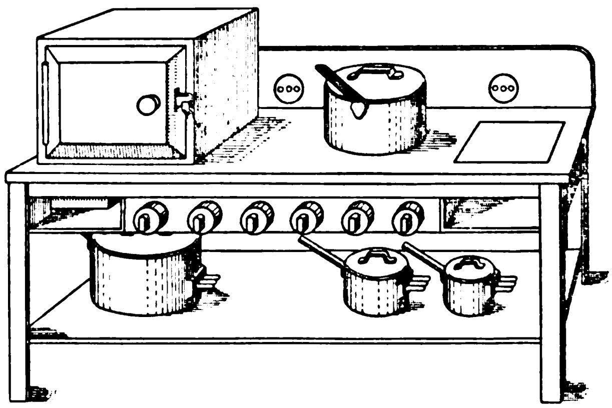

FIG. A.—Suggested cooking table with utensils with 3-heat self-contained elements, portable oven, grill and closed boiling-plate, designed to secure speed with safety and economy.

this can easily be done although one fire is fixed. On the other hand, too much stress cannot be laid on the convenience obtainable from the portability of the electric fire, for this is one of the unique advantages of electric fires, particularly when employed for occasional use, as in bedrooms, etc.

The disadvantage mentioned by Dr. Ferranti of having nowhere to throw odds and ends is more apparent than real. In summer such odds and ends would not be tolerated in the fireplace—the coal fire as a handy receptacle is available only in winter. Perhaps we can learn a lesson from Mr. Baldwin. In his rectorial address to the Edinburgh students the Prime Minister admonished his hearers to learn from the sailor who refrained from spitting on the deck. Thereby the sailor not only avoided giving unnecessary labour, but also strengthened his self-control. (It was not stated that the sailor refrained from spitting.) I agree that the value of the service of the electrical supply to me is much greater than what I pay for it. We owe Dr. Ferranti a debt of gratitude for his interesting account of the efficient use he is making of the heat in

the jacket water of his engine. The one serious criticism of his scheme seems to be its high capital cost.

The Association of which Miss Haslett is director can do much to disillusion women about the high cost of electricity for domestic purposes, and to educate them as to its advantages. Too much emphasis cannot be laid on the necessity of a good maintenance service. Users must be assured that they will not be let down.

Everyone will be obliged for the important and authoritative evidence put forward by Prof. Barker, who has given such close attention to this subject. I think, however, that he carries economy in the home too far. Surely we are not to be asked to run our homes like a factory or an office! I cannot see how the costs given in the paper can be misleading, for the corresponding consumptions are also given. The success of the scheme clearly depends on the tariffs, and judging by results the costs are about the same as given by other speakers using other methods. In what way is it misleading to give the public the impression that a 10-roomed house can be run on electricity for £40–£50 a year? It is being done in Glasgow, and the ½d. per unit tariff exists in many other cities. From the heat units tabulated by Prof. Barker (Table A) the well-to-do man is allowed 11 million, the artisan 3 million, whilst I use 8 million—a figure in close agreement with Prof. Barker's experiments. Thus my mode of living is quite normal on Prof. Barker's own showing. If anything, Prof. Barker has rather proved to the populations of Manchester, Liverpool, Hastings, Sheffield, Wolverhampton, Worcester, Leeds, etc., that they can do the same as people in Glasgow if they wish. I do not agree that the losses in heating up a given quantity of water in 10 hours are 10 times greater than the loss in heating up in 1 hour. I fail to see any connection here. Moreover, the costs have not been based on rates of ⅜d. or ½d. per unit, but on the overall rates of 0·637d. for the total consumption and 0·791d. for the day consumption. Prof. Barker asks not for costs but for the total B.Th.U. per annum per person expended in producing the various services. Surely Table 2 satisfies these requirements, for has he not obtained therefrom figures for Table A?

I am much indebted to Major Henrici for the figures in Table B, particularly as items such as kindling and matches are included. It is balance sheets such as these that are necessary for proper comparisons to be made. The case cited here serves to show that with the rates in question the several costs are competitive. Without wishing to exaggerate what electricity can do, I can assure Major Henrici that the saving in labour is very considerable.

Valuable comparisons are given by Dr. Margaret Fishenden, showing again that my results are reasonable and competitive. The figures given by Miss Fishenden on costs of the several services are much appreciated. With respect to the efficiency of electric boiling-plates, the figures which I gave were obtained from tests made by me for heating about 2 to 3 pints of water from cold. The testing of boiling-plates is a very difficult problem indeed, and the very greatest care must be taken to get correct results. Moreover, the conditions of the test must be laid down with the closest precision. It is hoped that my results will shortly be published. No discomfort was caused from insufficient heating, and it was always possible, by placing fires where they were needed, to avoid unpleasant sensations due to unequal heating.

In reply to Mr. Gooch, it is not clear in what way the electric fire offers less comfort than the coal fire. The human body needs warmth, preferably in the form of heat rays, and this the electric fire gives. Is it not almost asking too much of the all-electric house that it should show great financial advantage over the ordinary house? If it is as good financially we ought not to complain, for there are many non-financial benefits which improve living conditions.

In reply to Mr. Coxon, there is a great deal to be said for the ideal of moving away from the city into rural districts. The lack of rural and railway electrification compelled me to build my house within the boundaries of a city instead of among some of the most delightful country in the kingdom.

In reply to Major Carter, not only do I find an irrepressible tendency to dispense with the grids of the boiling-plates, but with the boiling-plates also. I trust that these will soon be replaced by more efficient vessels, such as pots with built-in elements. At the same time I do not understand why Major Carter's cooking consumption should be so large, especially as grids were dispensed with. I am inclined to believe that the storage tank is relatively more efficient than Major Carter estimates. It must be remembered not only that hot water is distributed in the house, but that the consumption in the paper includes a certain amount of emergency heating of water. Electric fires of the modern types have given remarkably little trouble.

In reply to Mr. Driver, it may not be long before electric appliances for cooking will be free from imitation. Already light, low-consumption aluminium ovens are on the market. The improvements to the boiling-plates consisted in raising the elements, lightening the grids and blackening the bottoms of the cooking utensils. Self-contained utensils need not be very heavy—no heavier, say, than black pots used for coal fires. Possibly the aluminium utensil has spoilt us somewhat. The cost of cooking appliances as outlined in the paper (light oven, self-contained cooking utensils, cooking table with grill and an enclosed boiling-plate) seems to be about the same as the cost of an electric range of the table type. A thermostat could easily be fitted to the hot-water tank, and probably would be in future designs. Mr. Driver's remarks show, however, that he understands my position too readily to expect me to introduce any unnecessary source of trouble. Without wishing to indulge in heroics, caution is natural when one has his " back to the wall." A trial of two tanks was made, and it was found better to use one only. If no rebate is obtainable for night load, there is a strong inducement to have a low-consumption tank continually in circuit. Efficient lagging, however, is more than ever essential where energy is not cheap. Thus any tank in which the water attained a steady maximum temperature of, say, 150° to 200° F. when no water was drawn off would have very large losses. Mr. Driver's remarks about contractors will be widely appreciated.

Prof. Fortescue is correct in saying that care is needed in an all-electric house to prevent waste, yet my figures do not represent "stint" in any way. It is not unreasonable to request that hot water be not allowed to run to waste and that boiling-plates and fires be switched off when not required. Already many cities have the same favourable rates as Glasgow, and it is to be hoped that rural districts will soon be in a similar position.

I agree with Mr. Grierson that flexible cords across the floor are inconvenient and dangerous. Much can be done to avoid this by spacing the sockets round the rooms and placing the appliances near, though not necessarily close to, the walls. The panel system described is full of interest, but I am not able to say whether this method of heating would be acceptable in homes. The table given by Mr. Grierson is very instructive and it is hoped that the figures given in the earlier part of my reply will show that the artisan's home can also be worked all-electrically.

It is welcome news to hear from Mr. Harmer that blackleading is unheard-of now. The speaker's coal fire which produces less dust than an electric fire must be almost unique; if, in addition, it would not pollute the outside atmosphere, neither neighbours nor anyone else would have much to complain of. With such fires the advocates of economy would get a cool reception. It is not myself but my critics who speak so much about garbage disposal—on this point Mr. Harmer and myself are in complete agreement. Let the rate collectors collect the refuse, and if they wish to burn it for its fuel value, good will result. I had no intention of offending women in my remarks on cooking. The fact is that many women do find cooking unattractive. The oven thermometer and the clock, combined with the cleanliness of electric utensils, should introduce new ideas about cooking and thereby make it more attractive to many intelligent women (and men) who, whether they like it or not, must do it. However much I may agree that "any woman worthy of the name takes a pride in cooking," this is the type of remark which in my opinion would be "uncalled for" in advocating scientific cooking. I do not know in what way lamp fires are better radiators than hot-wire fires—radiation is a function of temperature difference. It had not occurred to me that my distribution board makes my house a showroom, nor is it clear to me how 4 ways could satisfactorily replace 31 ways.

In reply to Mrs. Matthews, the hiring out of costly appliances (on a commercial basis) is becoming more and more common, but there are many articles now on the market that have been thoroughly tried out. Many of the queries raised might well condemn conversion to electricity on purely economic grounds—it is when one attaches importance and value to comfort, cleanliness and labour-saving healthfulness (to use this lady's own words) that one begins to regard the problem in the same way as other problems in life, such as clothing, holidays, etc.

In reply to Mr. Tremain, I have not found it needful to devote any time to the development of vacuum cleaners for the home. There are many reliable cleaners on the market, and the possible existence of an objectionable odour has not previously been brought to my notice.

In reply to Mr. Moffett, supply undertakings appear to be able to cope with a fair domestic load without increasing their plant—this would seem to be the basis of their keenness in pushing low tariffs for such load. I have made the efficiency (from coal) of my fires appear as low as possible—even now the figure is no worse than that of a common coal fire. The coke-fired boiler with 70 per cent efficiency must be unique. Yet with all my inefficient appliances many speakers have shown that the total costs are no greater than with other modes of running a house.

In reply to Mr. Jennings, it seems to be a pity that a great, modern city like Birmingham should introduce its new domestic tariffs at ¾d. per unit when ½d. per unit has been adopted by so many other municipalities. Surely this fact alone will hinder many people going the whole way—the high tariff is the only danger apparent to me in the "all-electric" idea. I would ask Mr. Jennings seriously to consider how far it is justifiable to use electricity in the home when the rates are such that it is too costly to use for everything.

I find myself practically in complete agreement with Mr. Wilson. I have included the sketch of my idea of an electric cooker in Fig. A on page 330. Doubtless a much more efficient oven than the present one can also be built.

I can only ask Mr. Joseph in return why "any" house needs a scullery. What poor efficiency to use a scullery for only a few hours per week. Washing with electricity can be done without filling the place with steam, by proper heat control. If my example appears extravagant, it has been shown by speakers in the discussion that an all-electric house can be built cheaper than an ordinary house. Every care was taken to avoid unnecessary expenditure, but a sound job was insisted upon.

In reply to Mr. Rawll, by "under-running" lamps is meant running them on a voltage lower than the rated voltage, the intention being to reduce renewals by lengthening the life of the lamps. For this to be effective, of course, the cost of energy must be small. Mr. Rawll points out the objection to geysers, and it is clear why preferential tariffs cannot be expected for such appliances. Surely with a loading of only 6 to 7 kW, merely a trickle of hot water would be obtained. It is hoped to include a daily load curve for winter in the reply to a later discussion. Possibly the most practicable way to balance the load would be to connect a similar house on the other side of the system. As far as I am aware, the local substation is not inconvenienced by my load.

Many readers will be indebted to Mr. Dean for his pioneer work and for his courtesy in permitting Mr. Milne to publish the comparative capital costs of the ordinary house, the electric plus one coal-fire house and the all-electric house. It is to be hoped that the Birmingham Electric Supply Department will encourage the scheme.

The comparative figures given by Mr. Milne are just what architects and other interested people need. The care with which the figures are given inspires

confidence, whilst the costs of electric appliances can easily be added, as these are well known. Of the £66 saved in building the all-electric house, some £16 to £22 will presumably go in wiring, leaving, say, £44 to £50 for electric appliances, which should be ample, especially as some of them would be hired. Apparently, therefore, the total costs would not be very different for the three different types of houses. Similarly the cost of my house could have been reduced to about that of an ordinary house by omitting chimney breasts, etc. The average weekly consumption, estimated at 100-120 units, should be enough for 5 or 6 persons in the household, and it is hoped that electrical energy will be obtainable at an overall cost of about ¾d. per unit.

In reply to Mr. Jones, it is probably true that leaving one coal fire per house will not reduce the smoke nuisance in winter. Perhaps some scheme could encourage the all-electric idea in densely-populated areas.

In reply to Mr. Longman, the quick-break switches worked by the toe are very satisfactory. Switches were apt to get damaged during building, but since they have all been put in order there has been practically no trouble. The main heater for the tank is at the bottom, the three-heat rotary switches being placed half-way up for convenience. Fifteen gallons of hot water per person per day may seem ample, but some people clamour for more. The cooking consumption —1·27 units per person per day—is perhaps nearer the average figure than the usually quoted 1 unit. However, there seems to be no reason why this figure should not be reduced to about one-half.

In reply to Mr. Moss, it is doubtful if the load on the house ever remains at 50 amperes for any length of time. The switch is so robust that I should not hesitate to overload it by 100 per cent for a short time. The I.E.E. rules allow 3/·036 cable to carry 10·3 to 12 amperes—how is it then overloaded with a 2- or 3-kW, 250-volt fire? The 15-ampere switch is the nearest and proper standard. The lighting circuits are not wired so much for heating as for voltage-drop, but they can be safely used for any appliances. I am glad that Mr. Moss agrees that tough-rubber cable makes the best job for bells. Would it not then be better to use it and stop people saying that electric bells are always going wrong? True, the wash-boiler takes longer than the washing machine to do the same work, but it is quite satisfactory for a small household and costs perhaps one-quarter as much as the machine. No trouble has been experienced from dust in the drying-closet—even if this were so, the air could easily be filtered at the intake. Because I have tried to do the work properly, it is a mistake to suppose that money has been spent freely.

The rates quoted by Mr. Mott are doubtless out of the question for all-electric artisan homes. Lighting and cooking alone seem to be possible.

It is pleasing to hear from Mr. Carter that a consumer of 10 000 units per annum can get his energy at 0·56d. per unit. Flexible tough-rubber and ordinary cables are on the market.

In reply to Mr. Hefford, unless some inducement be given to the consumer to install a storage tank and to heat water during the night, it is fairly certain that it will become part of the peak load, and possibly in the form of, say, a 30-kW geyser. Why not? Now there is no difficulty about the switching. A thermostat and time clock would do all this automatically—nothing could be simpler. In my opinion, separate cooking utensils would be simpler than boiling-plates, and there need be no flexible cables at all—all utensils would be interchangeable. Further, our success will not be complete in cooking until we have discovered and applied the true merits of electricity—even though this may entail educating the public. This point applies also to the portability of the fire. There are other functions to perform in the bedroom besides undressing —for example some folk use a washstand, others a dressing-table, yet others, both. Surely it is better to have a portable fire than a portable washstand or dressing-table. With regard to preferential rates for night load, my argument would be as follows. In order to induce certain classes of consumers to take night load, it must be remembered that such consumers are not tied down to take their energy at any stated time. If, therefore, such processes are to be carried on at night time, some concession will have to be made. There is no need to limit the application to water-heating; nor need such concessions be extended to processes which must take place during the night—after all, the station has to be kept running for these consumers, often at a big loss. It will be interesting to see whether the open coal grate now being installed in the new houses in Leeds, primarily for burning rubbish, will really be used for that purpose. Frankly I doubt it. Why should a fire be lit in an electric house in summer just to dispose of "certain classes of rubbish within a few hours of it being formed." Unless Leeds folk differ much from other folk the inspection staff of the Medical Officers of Health must have a busy time, especially in summer. With regard to smoke, which is the greatest nuisance in winter, I cannot see how the artisan can be expected to reduce his smoke in winter, provided he is given his coal fire. As stated in the paper, there are 6 persons in my household. The vertical flue is 9 in. × 9 in.; the inlet is the size of two bricks and is adjustable; the outlet is a grid 6 in. × 7 in. and is always open.

In reply to Miss Hancock, black priming paint is suitable for blackening the bottom of utensils, but it is hoped that in the near future such makeshifts will be superfluous. I certainly should not advocate them for general use. It is interesting to learn that energy is being offered at a fraction over 1d. per unit. If the house is to be closed during the day, 6 000 units per annum seems to be a very liberal estimate. For drying clothes, the fan is probably more useful and certainly more economical than the radiator.

In reply to Mr. Hodsman, continuity of supply is all-important—to cut off the electricity supply between noon and 1 p.m. every Sunday is intolerable. As far as I am aware, the supply to my house has not been cut off since I entered on the 12th July, 1924. Ventilation is certainly important, but here again facts should not be overlooked. At certain periods many people have neither fires nor open windows—this condition is widely tolerated, as is also the sleeping in rooms with

closed windows. I do not agree with this practice and my method of ventilation has proved satisfactory. Coal fires often produce too much draught and the feet suffer in consequence. An open window may well be advisable when there is no fire, whatever the type of house. The ventilation question ought not to give any trouble if properly attended to. The householder should be able to decide for himself whether he will use electricity for all purposes—though public opinion in the future may place restrictions on the burning of raw coal. It is hard to see why householders should be asked to shoulder the burdens of vested interests (the term "vested" seems to be more justified than "national"). In what way is the electrical engineer interfering with the natural development of the industries of carbonization? As yet there would seem to be no low-temperature process developed on a commercial scale, and it is quite possible that power engineers may be first ready with economical methods of producing liquid fuels and other necessities of civilized life. Perhaps the future generating station will prove the best means of treating coal and utilizing gas and coke; and it is certainly going too far to say that electricity is being applied to purposes for which it is not naturally fitted. As regards America, it may well be that the gas industry is much less developed than in Great Britain. With respect to Germany, Mr. Hodsman should know that hydro-electric power is often more costly than steam power. As for the public, since when was it the custom for the German Reich to look after the domestic consumer? Nationalization, or socialization, as understood in that country, has not brought cheap electricity to the individual. Mr. Hodsman's argument about the householder subsidizing the power station is apparently what he is advocating for the gas industry, so that the poor consumer would have to pay in any case. It is not admitted, however, that the domestic coal user is subsidizing the electric industry. The fuel used by power stations is not suitable for domestic uses and is bought in large quantities without high distributive costs. Whilst there is no intention to brush aside national problems, it would be stupid to arrest development because of academic discussions.

The criticisms of Mr. Buist are well worthy of attention, as they contain much solid foundation. The use of a coal fire in an artisan's home to furnish an abundant supply of hot water is probably a stronger argument than that based on refuse and romance. From figures given earlier in my reply (p. 330), I have tried to show that the all-electric case is not hopeless for the artisan.

The question of tariffs raised by Mr. Thwaites cannot be so easily dismissed. If the supply engineer is convinced that much of the domestic load does not entail increased capital outlay, he is right to develop his load accordingly. Glasgow has dropped the ¾d. limit—there is no logical justification for a limit of this nature. I should not underrate the importance of the arguments on the ultimate effect of a large domestic load, but are we not looking too far ahead? Who knows what the position will be when the all-electric house becomes general or even common? Should not the cooking consumption of ½ unit per person per day read 1 unit? The drying closet is drawn to scale in Fig. 3 and is as high as the kitchen. The fan is near the ceiling.

I agree with Mr. Watson that it is nicer to have food cooked in the kitchen and eaten in the dining-room, but facts ought to be faced. Mr. Watson himself speaks of "a sort of kitchen sitting-room" in the houses for which he is responsible. Is this not the practice in most houses throughout the country? Even in larger maidless houses, are there not many minor operations which can be done conveniently and more comfortably in the warm living-room? Such operations can be carried out in nickel-plated utensils (kettles, percolators, pots, etc.). Obviously the kitchen must be used when much cooking is to be done. Mr. Watson's method of arriving at a tariff does not seem to be logical; also the comparison was made only for cooking.

In reply to Mr. Carr, surface wiring has not been used in the house. It is possible that the preference for conduit may give way to more modern and cheaper methods of wiring. Whilst I do not advocate blackening the bottom of cooking utensils, I disagree with most of Mr. Carr's remarks in this connection.

In reply to Mr. Sills, I do not consider 12 minutes to be too long to boil 3 pints of water, nor can I see how any improvement would result with a 2½-kW boiling-plate. Mr. Sills really needs a heavily-loaded geyser. With my switches, practically all bending is avoided. There is a danger in throwing too much heat down—carpets may be scorched or floorboards may be warped.

An incinerator would doubtless solve Mrs. Lamb's difficulty, though I do not know many people who would use it. An all-electric kitchen with white-enamelled basins, nickel-plated and copper utensils, electric fire, polished woodwork, etc., is a very different place from the ordinary kitchen. Moreover, there is no difficulty in keeping such a kitchen free from dirt or smell.

I disagree in general with Mr. Philip's remarks on boiling-plates—the trouble is really deeper and affects the principle employed. Immersion heaters are said to cause certain foods to burn. Before entering the house, emergency devices seemed to be desirable, but experience has proved the contrary to be the case. From the results obtained, it is hard to see how water-heating and continuous room-heating are extremely uneconomical.

It seems to me that if Mr. Lamb once grants the one coal fire, he not only loses the main source of domestic revenue but really defeats his own argument. So long as a consumer goes the whole way, the supply undertaking knows its position clearly, respecting mains and plant. The occasional user is the uncertain factor. On a cold or foggy day, when the peak loads are worst, many of these occasional fires will be used to assist coal fires, to warm kitchens, bedrooms, and so on. This is inviting trouble, and eventually it will entail additional plant with small earnings. To my mind, Mr. Lamb's facts all favour the all-electric house.

In reply to Mr. Eccles, the paper describes an all-electric house and shows that such a house can be run economically. It is not part of my profession to

investigate the most economical way of running a house—which probably I should run away from—nor to design kitchens, larders and so forth. Suffice it to say that none of the imagined faults seems to have been observed by anyone who has lived in the house. Doubtless many pioneers have passed through the same experience as himself, and it is possible that people nowadays are benefiting by their efforts. Perhaps Mr. Eccles was asking too much of electricity, but it is a pity that he gave up the fight, especially as supply undertakings are beginning to appreciate the need of a good maintenance service.

In reply to Mr. Watson, cold water enters at the bottom of the tank as hot water is drawn off at the top. Very little mixing occurs—of course the inlet water should be suitably baffled. It is a simple matter to place rubber-covered cable in open conduit in the short, exposed runs where a nail is likely to be driven into the plaster.

It is interesting to learn from Mr. Lunn that in Manchester a consumption of 6 495 units works out at 0·673d. per unit. In Glasgow this was about the cost per unit for a consumption of 16 584 units, of which 6 043 units were charged at 0·375d.

CROSS-BREAKING STRENGTH, STIFFNESS AND OIL ABSORPTION TESTS FOR HARD COMPOSITE DIELECTRICS.

SUPPLEMENT TO "DIRECTIONS FOR THE STUDY OF HARD COMPOSITE DIELECTRICS" (REF. B/S1).*

[REPORT (REF. B/S2) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

PREFACE.

In Clause 8 of Ref. B/S1, the cross-breaking strength is expressed in terms of a constant k derived from the usual formula, but requiring division by six to give the stress per unit area.

It has been suggested that it would be more convenient if the clause were modified so that the cross-breaking strength were expressed in terms of stress per unit area, also the units being the pound and square inch. The adoption of these units will bring the revised clause into line with the usual practice of the E.R.A. with other classes of insulating material.

To meet the views expressed above, Clause 8 of Ref. B/S1 has been revised as shown herein.

The opportunity has been taken to include a test for stiffness or rigidity which has been adopted in the study of other classes of dielectrics. This does not involve a separate test, as the necessary observations can be readily made whilst the cross-breaking strength test is being carried out.

When Ref. B/S1 was issued a suitable test for the determination of the effect of oil on hard composite dielectrics had not been developed. As the result of investigation the oil absorption tests given herein have been adopted by the Association.

REVISED CLAUSE 8 OF REF. B/S1.

Note.—In the following clause pounds and inches have been adopted so as to conform to the usual practice of the E.R.A. with respect to other classes of insulating material.

* See *Journal I.E.E.*, 1922, vol. 60, p. 565.

(a) Cross-breaking Strength at Normal Temperature.

The material shall be tested at a temperature from 15° C. to 20° C.

The specimen shall be of the shape and dimensions shown in Fig. 9 (see Ref. B/S1) and shall be set up for testing generally in the manner indicated in Fig. 10 (see Ref. B/S1). When it is impracticable to obtain a specimen of the dimensions shown in Fig. 9, the alternative specimen shown in Fig. 11 (see Ref. B/S1) may be employed, which shall be set up as indicated in Fig. 12 (see Ref. B/S1). The load shall be increased gradually at the rate of 20 pounds per minute until the specimen breaks.

The cross-breaking strength at normal temperature is computed from the following formula :—

$$C = \frac{6WL}{BD^2}$$

where C = cross-breaking strength in pounds per square inch.
W = breaking load in pounds.
L = cantilever length in inches.
B = breadth of specimen in inches.
D = thickness of specimen in inches.

(b) Cross-breaking Strength at Grade Temperature.

Note.—The test is carried out as described in Clause 8 (*b*) of Ref. B/S1, and the cross-breaking strength is computed as shown in (*a*) above.

Stiffness or Rigidity.

Note.—The following additional test is suggested for application to hard composite dielectrics. The necessary observations can be readily made whilst the cross-breaking strength test is being carried out.

(*a*) *Young's Modulus at Normal Temperature.*

The material shall be tested at a temperature from 15° C. to 20° C.

The specimen shall be of the shape and dimensions shown in Fig. 9 (see Ref. B/S1) and shall be set up for testing generally in the manner indicated in Fig. 10 (see Ref. B/S1). When it is impracticable to obtain a specimen of the dimensions shown in Fig. 9, the alternative specimen shown in Fig. 11 (see Ref. B/S1) may be employed, which shall be set up as indicated in Fig. 12 (see Ref. B/S1).

A measurement shall be made of the distance of the unsupported end below datum point as follows :—

An inside micrometer shall be clamped above the stirrup and connected to a battery and low-reading voltmeter, the circuit being completed through the stirrup. The micrometer screw shall be turned until the circuit is closed (as indicated by the voltmeter) and the micrometer reading shall then be taken.

Small equal increments of load shall be applied and the corresponding increments in deflection measured immediately. Each increment of load shall be applied as soon as the deflection for the previous load increment has been read. Readings shall only be taken for the range during which the increment of load is proportional to the increment of deflection. The load at which the deflection departs from proportionality (yield point) shall be noted, and the stress, computed from the formula given in the revised Clause 8 (*a*) above shall be stated.

Young's modulus E shall be computed from the following formula :—

$$E = \frac{4L^3w}{BD^3y}$$

Where E = Young's modulus of elasticity in pounds per square inch.
L = Cantilever length in inches.
w = Average increment of load in pounds.
B = Breadth of specimen in inches.
D = Thickness of specimen in inches.
y = Average increment of deflection in inches.

(*b*) *Young's Modulus at Grade Temperature.*

A specimen similar to that employed in (*a*) shall be set up as described in (*a*) without loading, and a measurement shall be made of the distance of the unsupported end below datum point as before. The specimen shall be heated for two hours at the grade temperature of the material and shall then be loaded and the increments of deflection measured as described in (*a*).

Oil Absorption Tests.

Hard composite dielectrics intended to withstand insulating or lubricating oils shall be tested to ascertain the change in weight after a specimen has been immersed for 24 hours in the appropriate oil given below at the grade temperature of the dielectric.

Mechanical deterioration is accompanied by relatively high absorption or by loss of weight, but the investigator should report any observable changes.

The dimensions of the specimen shall be approximately 15 mm cube, or a sample of equal surface area (viz. 13·5 cm²) shall be tested. The test shall be carried out as follows :—

The specimen shall be weighed, immersed in oil at the grade temperature for 24 hours, then removed from the oil, rinsed with petrol and dried. The change in weight shall be expressed in grammes per sq. cm. computed on the surface area of the specimen. Three specimens of the material shall be tested, and the maximum, minimum and mean values of the oil absorption number obtained as described above shall be stated.

(*a*) Transformer oil which shall comply with B.S.S. No. 148 for Class A light grade oil.

(*b*) Lubricating oil, which shall consist of a mineral oil with 20 per cent of blown rape oil, and shall comply with the following specification : *

Specific gravity at 60° F. (15·6° C.) .. 0·92 (approximately).

Closed flash point .. Not less than 370° F. (188° C.).

Viscosity .. .. ..

Temperature	Time of outflow of 50 cm³ in Redwood viscometer, secs.	Absolute value, centipoises
200° F. (93° C.)	75	15
300° F. (149° C.)	38	7·5

Acidity, calculated as oleic acid .. .. Not more than 1 per cent.

Loss in 2 hours at 212° F. (100° C.) (determined as described below) .. Not more than 0·3 per cent.

The oil shall be free from mineral acid.

The loss at 212° F. (100° C.) shall be determined by heating 9 grammes of oil in a flat-bottomed porcelain dish approximately 2½ inches diameter and ¾ inch deep.

* This oil is a standard lubricating oil, and is readily obtainable.

THE VARIATION OF EFFICIENCY WITH SIZE, AND THE ECONOMIC CHOICE OF ELECTRICAL MACHINERY.*

By D. J. Bolton, B.Sc. (Eng.), Associate Member.

(*Paper first received 17th July, and in final form 23rd October, 1925.*)

Summary.

The paper consists roughly of two parts—an examination of the efficiency of electrical machinery of varying sizes, and an application of the results to the problem of economic choice. In the former section it is shown that wherever there is more than one kind of loss a large machine will have a higher efficiency than a small one, by an amount which is roughly predicable. It is further shown that this efficiency can be maintained with little or no diminution when the machine is suitably under-run, depending on the kinds and proportions of the losses. This makes it possible to calculate the cost of improving the efficiency of a given service to any required degree through the employment of larger plant than is physically necessary.

Applying this to the selection of apparatus to fulfil a given service at the least total cost, the cases considered are squirrel-cage induction motors, small d.c. motors and single-phase transformers. Placing all items on an annual basis, the rates of change of the various charges with reference to the frame size are worked out for a range of sizes in each of the three cases. These rates of change form an index by which the most economical size can readily be estimated for any conditions of service, and the method of doing this is fully explained in the paper.

The results suggest that where the hours of service are long or energy is expensive a far larger or more efficient machine is justified than would normally be employed. Where such improved efficiency is proposed, the method here developed makes it possible to calculate the particular degree of improvement which is economically justified in any case. Such a calculation should be an essential feature of the design (or failing this, the selection) of all apparatus for long-hour service.

Table of Contents.

(1) Introduction.

An attempt is made in this paper to develop a general method of choice of electrical machinery on economical grounds, the word "machine" or "structure" being used in the widest possible sense to indicate any piece of apparatus performing a definite tangible service and capable of being independently chosen. For this purpose it is assumed that the service is in all respects fixed and known, i.e. the type of machine, output, speed and other particulars as well as the hours of service and cost of energy. It will further be assumed that there is no qualitative difference between the various alternatives available, so that the choice is merely of the most suitable size.

A warning should be made at the commencement, that just as economics is a less exact science than physics, so the branches of engineering based on the former will inevitably be less exact than those based on the latter. With this qualification in mind, two rough generalizations may be made with regard to electrical machines of all types except the very simplest. These are, first, that a large machine is usually characterized by a higher efficiency than a small one of the same type, and, second, that this efficiency can usually be maintained even when the large machine is under-run so as to give a smaller output.

In order to give a precise meaning to the above it will be necessary to define exactly what is meant by a "larger" machine and by "under-running": but, leaving this for the moment, it will be evident that if the above statements are true there are two entirely different methods of choosing a machine to perform a given service. The normal method is to select a machine having just sufficient iron, copper, etc., so that (when giving the output aud occasional overloads required) the temperature-rise, centrifugal and dielectric stresses, the commutation and the regulation are all kept within satisfactory limits. This may be described as the *physical* choice, and it will be obvious that in no case can a machine be installed smaller than this size. But if a bigger machine would have a higher efficiency at the required output, it might be more economical in the long run to install it for this reason, and such a decision would then be a specifically *economic* choice. As the two sets of criteria are quite unrelated it is evident that both calculations should be made, and the machine chosen should be the larger of the two, whichever that is.

An electrical machine may be compared in this respect with a leaky vessel such as a slightly porous balloon. If too big a load is put upon it, it will burst and be destroyed, but long before this point is reached considerable leakage is taking place. Hence, if the cost of the inflating material is great compared with that of the balloon material, it may be cheaper not to load it up to its physical limit.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

A single instance will serve to show how considerable is the cost of this leakage in comparison with the cost of the plant itself. A 40-h.p. 1 000-r.p.m. 50-period squirrel-cage induction motor having an efficiency of 88·5 per cent can be bought for about £70 at the present time. Such a machine, running for 8 hours a day and 300 days a year with energy at a uniform price of 1d. per unit, in a useful life of 20 years consumes nearly £7 000 worth of energy—equivalent in cost to 5 new motors every year of its life. Moreover, whilst the bulk of this energy is transformed into useful work, the sum actually wasted in machine losses amounts every year to £38 15s.—more than half the price of the motor. If this efficiency could be improved even by so much as ½ of 1 per cent the energy saved would be worth £2 a year, which could be capitalized over a 20-year life as equivalent to the lump sum of £25—sufficient to pay for a very generous increase in the copper and iron sections.

The small amount of attention paid to efficiency in its economic aspect is due very considerably to the difficulty of calculating, in any particular case, what degree of efficiency improvement would be worth while, and (when calculated) the difficulty of requisitioning such a machine. These two difficulties have been attacked in this paper on the lines of establishing a general criterion of the economic degree of efficiency, visualizing for this purpose the employment, not of special high-efficiency machines, but of standard machines built for a greater output than that required.

(2) Physical Ratings—Heating and Densities.

It was stated above that before attempting to prove the generalizations there made it is necessary to define the terms used, since it is impossible to study the effect of taking a less than normal output from a given machine until one knows what determines the normal output. The physical rating of any given frame may be defined as that output which can be taken, for the period and under the conditions specified, without the temperature-rise exceeding some figure which is considered safe from the point of view either of internal deterioration or of external danger. In addition, there is frequently an overload requirement for a short period, which may be a question of commutation or electric strength as well as temperature, and there is sometimes a requirement as to regulation, but for the most part it may be said that size is roughly determined in the great majority of cases by temperature limits.

It will be noticed that not one of the above limits concerns either the current or the flux densities employed, and yet the surprising thing is that over a wide range of sizes of any particular type of machine, a given temperature-rise corresponds fairly closely to a given set of current and flux densities. This is one of those coincidences which are normally taken for granted, but which are not nearly so inevitable as they seem.

The close correspondence which exists between densities and temperature-rises is illustrated by the fact that a d^2l formula is frequently used to estimate the frame size of a rotating machine to comply with a temperature specification, although the formula that output is proportional to d^2ln is based on the assumption of fixed densities and has no connection with temperature-rise. In order to discover why the two largely go together, it will be well to take actual cases, bearing in mind that with given densities the losses are each proportional to the volumes of the active materials.*

Taking as a starting point the assumption of fixed current and flux densities, consider first a constant-speed rotating machine. It is easy to show that if the specific electric loading is fixed, the output of such a machine is proportional to the d^2l of the armature or rotor, so that if d and l are both doubled the output will be increased 8 times. On the other hand, the amount of iron in the magnetic path and the copper in the slots and end connections will only be slightly more than 4 times what they were, and hence the losses † will only be increased in this smaller ratio. As the rotating surface is just 4 times what it was and the peripheral speed is greater, the machine will thus be able to dissipate these losses with approximately the same temperature-rise.

Hence the correspondence between densities and temperature-rises is in a sense a happy accident ‡ due to the fact that the output (with fixed densities, speed, and dimensional proportions) is proportional to rotor volume (or d^3) whilst the losses and cooling capacity are both proportional to surface (or d^2).

(3) Efficiency and Size.

Two things result from the above. Not only can designs be carried out on a basis of fixed current loadings and flux densities for a wide range of machines complying with a single temperature specification, but it also follows that the efficiency of a large machine must always be inherently better than that of a small one, and by a definite and ascertainable amount. For if the output is proportional to d^3 and the losses to d^2 the ratio (losses/output) will be proportional to $d^2/d^3 = 1/d = 1/\sqrt[3]{\text{Output}}$.

The extent to which this is borne out in practice can easily be discovered from any range of machines of the same type. Thus, in the author's previous paper § a range of shunt motors from ¼ h.p. to 15 h.p. was listed, together with their efficiencies, from which can be calculated the ratio (losses/output), since this is equal to the reciprocal of the efficiency, minus one. Multiplying this figure by the cube root of the output (h.p.) gives a fairly uniform figure of approximately 0·4 in each case (see col. 8 of Table 3 on page 345). Not only is there no perceptible tendency for this figure to vary with the machine size, but also the range of fluctuation is remarkably small, i.e. 25 per cent for a change in size of 60 times. Similar figures are here listed for a range of

* With constant frequency and flux density the iron losses can always be expressed per cubic centimetre of iron, whilst the copper loss $= I^2R = \frac{I^2l\rho}{A} = \left(\frac{I}{A}\right)^2 lA\rho$, so that this loss is also proportional to volume (lA) when the current density (I/A) is constant.

† The friction and windage losses are more difficult to estimate. The former will increase less than proportionally with the increase in weight, whilst the latter will increase both because of the surface and because of the greater peripheral speed. These losses will therefore also be slightly more than 4 times what they were, but it will be noted that in any case they dissipate themselves with little or no effect upon the winding temperature-rise.

‡ If the word "accident" be objected to, the position may be put the other way round by saying that in the design of a rotating machine the active materials are grouped round a cylinder to an approximately fixed depth or density, so that the losses shall always keep pace with the cooling powers of the cylinder.

§ *Journal I.E.E.*, 1924, vol. 62, p. 901.

squirrel-cage motors (col. 8 of Table 1 on page 344), and a similar constant connection is obtained, although in this case there seems a tendency for the figure to increase with the frame size, thus suggesting that the root index should be somewhat higher than 3, due possibly to an increase in the specific electric loading.

In the case of transformers, if a uniform winding depth or loading were maintained as in rotating machines, the same law would hold, and the output would be proportional to the volume, or d^2l, of the iron core. But as it is customary also to increase the winding depth proportionally with the increase in the core (so using the whole of the " window " space) the output will go up at a greater rate than this.

By considering a simple transformer such as the ring type, it is easy to see that if d is the core diameter and if all the dimensions are varied in the same proportions, the iron cross-sectional area will be proportional to d^2 and the copper winding space to d^2, so that the output will be proportional to d^4, whilst the weight of both copper and iron, and therefore the losses, will be proportional to d^3. Hence the loss ratio (losses/output $= 1/\eta - 1$) is proportional to $d^3/d^4 = 1/d = 1/\sqrt[4]{\text{Output}}$. In a similar way it has been proved for all the commercial shapes of transformer, both shell and core types, that if all the dimensions are increased in the same ratio to a times their previous value, the output will be a^4 times and the loss ratio will be $1/a$ times its original value.*

It is therefore evident that if the heat-dissipating surface were only that of the transformer iron and windings, the temperature-rise would tend to get steadily worse as the size increased, since losses are proportional to d^3, whilst surface is only proportional to d^2. This is what actually happens in the case of air-cooled transformers, and explains the virtual upper limit of size unless the densities are correspondingly reduced. In the case of oil-immersed transformers the radiating surface is that of the whole tank, and it is comparatively easy to proportion the size of tank and amount of oil either to the kVA capacity or to the actual watts lost.

The above statements must be modified slightly on account of change in the space factor. Thus the effect of doubling d will be to quadruple the winding space and to allow 4 times as many turns of the same size of wire. If, however, the current is to be increased rather than the pressure, a larger section of wire will be employed, giving a better space factor ; so that the ampere-turns will be increased in the ratio of, say, d^3 rather than d^2. This will give an output of $d^2 \times d^3 = d^5$ times, an iron loss of d^3 times, and a copper loss of d^4 times. Hence the total losses (which can, of course, be distributed as desired) will lie between d^3 and d^4, say $d^{3\frac{1}{2}}$, giving a loss ratio proportional to $d^{3\frac{1}{2}}/d^5 = 1/d^{1\frac{1}{2}} = 1/(\text{Output})^{0\cdot3}$.

In confirmation of the above, the loss ratios $(1/\eta - 1)$ for the single-phase transformers listed in Table 4 were plotted logarithmically to a base of rated kVA, and gave an index of 0·31, and the amount of individual deviation is shown in the last column of Table 3. A similar line of three-phase transformers was also plotted and showed an index lying between $\frac{1}{3}$ and $\frac{1}{4}$; and, moreover, in each case the index showed a tendency to approach $\frac{1}{4}$ in the larger sizes, where the change in space factor would naturally be less marked. A further confirmation of the above reasoning was obtained in the case of the single-phase series by plotting (logarithmically) the iron cross-sectional area against the kVA output, which gave an index of 0·4, i.e. the iron cross-sectional area is proportional to $(\text{output})^{0\cdot4} = (d^5)^{0\cdot4} = d^2$, as it should be.

It is needless to point out that the generalized reasoning and the few examples here given are in no sense put forward as an exact proof of the law followed, and in fact the precise form of this law is immaterial to the main object of this paper. What is important is to note that the efficiency of the larger machine is inherently better and by a definite predicable amount, this amount being roughly given both for rotating machines and transformers in the statement that the loss ratio is inversely proportional to the output raised to a power lying usually between $\frac{1}{3}$ and $\frac{1}{4}$.

Another criticism which may be raised is that the process of explaining the index figure relating to transformers would appear to upset the figure arrived at for rotating machines, since in these also the space factor should improve with size. The two cases, however, are not parallel. In transformers the whole of the available window space is utilized, so that the space factor becomes a determining factor in the output obtainable from a given frame, whilst in a rotating machine a poor space factor can always be compensated for by increasing the slot depth : the limit here is not the space but the cooling capacity and therefore the electric loading.

(4) Efficiency on Under-running.

In what follows it will be convenient to define the maximum or rated output of a frame in terms of fixed current and flux densities, on the understanding that this will give approximately fixed temperature-rises. Such a definition gives a precise meaning to the two generalizations laid down at the commencement, and the first of these, namely that a large machine is characterized by a bigger efficiency than a small one of the same type, has been illustrated and to some extent proved in the foregoing paragraphs. It now remains to examine the second and more difficult proposition concerning the maintenance of this higher efficiency when the machine is under-run.

Unfortunately the simplest type of machine which can be used for illustration purposes—the " single loss " structure such as the electric cable—does not conform to either of these rules. In this case the larger machine, running at the same current density, has just the same efficiency as the smaller one, but, on the other hand, under-running *increases* the efficiency, so that the net effect (upon which any possibility of economic choice of size depends) is the same as with more complex structures. That is to say a larger machine used on a smaller load will have a higher efficiency than a smaller one giving its full capacity.

* A. P. M. Fleming and K. M. Faye-Hansen: *Journal I.E.E.*, 1909 vol. 42, p. 396.

One of the most useful classifications of the losses in an electrical machine is as follows :—

Losses dependent upon the current and virtually independent of the pressure.

Losses dependent upon the pressure and virtually independent of the current.

Losses independent of both current and pressure.

With this grouping the total losses can be expressed as

$$c_1 I^a + c_2 E^b + c_3$$

where a, b, c are constants, I and E the line current and pressure respectively, and a and b have each very approximately the value 2. In a similar way the efficiency can be generally expressed as

$$\eta = 1 - \frac{\text{Losses}}{\text{Input}} = 1 - \frac{c_1 I^a + c_2 E^b + c_3}{EI \cos \phi}$$

This may be illustrated by considering any rotating machine such as a d.c. shunt motor. The first group of losses, namely those represented by $c_1 I^a$, covers the armature copper losses. These are strictly proportional to the square of the armature current with constant resistance, but the difference between armature current and line current is not great, and, moreover, this discrepancy will probably be balanced by the positive temperature coefficient of the windings.

The second group of losses, represented by $c_2 E^b$ includes the whole of the shunt field losses and the iron losses, as can be seen by considering the effect of a change in pressure. Thus, suppose the line pressure to be halved, with the current and speed unaltered. The field losses, being equal to E^2/R, will be quartered, and the field strength, with constant permeability, will be halved. (If the permeability is not constant some field resistance must be introduced to bring the field strength down to slightly less than half what it was.) The back E.M.F. with the same speed can thus be made slightly less than half its previous value, so that with half the line pressure the difference between the applied and the back E.M.F. will be unaltered, and the same current will flow.

The flux density B is thus roughly proportional to the line pressure E, and, furthermore, it has recently been shown * that the iron losses of a d.c. machine can be most accurately assessed by coupling hysteresis and eddy losses together, and that they are very approximately proportional to B^2, that is $b = 2$ in the above formula. Finally, if c_3 represents the constant friction and windage losses, it will be seen that the whole of the losses have been accounted for.

It will be noticed that the " pressure " items are not strictly independent of current, owing to the difference between applied and back E.M.F., and for this reason the formula is most accurate when pressure and current are being varied simultaneously.

In the case of a series motor the field losses come into the $c_1 I^2$ group, and if the pressure alone is varied the field strength must be artificially changed to correspond. In the case of machines in which part of the current is induced, this latter will not be exactly proportional to the line current, but, in spite of these various discrepancies, the above formula, with $a = b = 2$, represents most cases with a sufficient degree of accuracy for economic calculations.

On the basis of this formula it will be convenient to group electrical machines into three classes according to whether they have one, two or all three of the possible kinds of losses. There will then be :—

Simple or homogeneous machines having only one kind of loss (i.e. copper or iron) ;

Complex static machines having two kinds of loss (copper and iron) ;

Complex rotary machines having all three kinds (copper, iron and frictional).

The nearest approximations in practice to machines of the first class will be found in current conductors and in iron-cored reactances. Thus in a cable (neglecting the slight dielectric losses dependent on E) the losses are proportional to I^2, and in a choking coil (neglecting the magnetizing-current losses dependent on I) the losses are proportional to E^2, i.e. in each case there is substantially only one class of loss.

The first point to note in a simple structure such as a cable is that the efficiency can always be raised by increasing that item of the supply upon which no losses are dependent. For, expressing the efficiency of a cable as $1 - (I^2R)/(EI \cos \phi)$, it is clear that this can be indefinitely increased by increasing E. As a rule, however, this method is inadmissible, since the pressure is fixed by the nature of the service. With regard to variations in current, the pressure remaining constant, it will be seen that the efficiency can be expressed as

$$1 - \frac{IR}{E \cos \phi} = 1 - \frac{I}{A} \cdot \frac{l\rho}{E \cos \phi}$$

where l is the length and A the cross-sectional area.

Thus, if the length is fixed, a large cable will have the same efficiency as a small one working on the same current density, but, on the other hand, if the large cable is under-run to give the smaller output, its efficiency will be increased. The possibility of economic advantage to be gained from the employment of a cable larger than that physically necessary was first pointed out by Lord Kelvin in 1881, and as the subject has been fully treated by subsequent authorities, no more need be said regarding this particular application.

Turning to machines of the second class, much the most important is the static transformer, the efficiency of which can be expressed as

$$\eta = 1 - (c_1 I^2 + c_2 E^2)/(EI \cos \phi).$$

It is obvious from this formula that if the transformer is under-run by reducing E and I in the same ratio, the full-load efficiency will be maintained intact, provided that the power factor is not affected. Thus any particular size of transformer can be regarded, not as something capable of giving a certain output, but as something having a certain efficiency. If a higher efficiency is required, then a larger transformer must be employed. A further point is that if at full load the two groups of losses are not equal, the efficiency

* *Journal I.E.E.*, 1924, vol. 63, p. 47.

can actually be improved by under-running, provided this is performed in suitable proportions. Instead of considering this in detail, however, it will be more advantageous to study the more general case given below, of which the transformer can be regarded as a particular instance.

The third class of machine (having all three varieties of loss) can be taken to include every type of rotating apparatus in which copper, iron and frictional losses occur. The efficiency can be written

$$\eta = 1 - (c_1 I^2 + c_2 E^2 + c_3)/(EI \cos \phi)$$

and it will be evident that if the line current and the line pressure are each reduced in the same ratio, the efficiency will fall owing to the presence of the constant frictional losses c_3. On the other hand, if either of the variable losses is bigger than the sum of the other two it will be possible to under-run in such a way as to reduce this larger loss and keep the efficiency as high as or even higher than on full load.

Thus suppose that the current loss is n times the sum of the other two, that is $c_1 I^2 = n(c_2 E^2 + c_3)$. Furthermore, suppose that it is desired to reduce the output, and therefore the input, in the ratio $1/m$ without impairing the efficiency, this reduction being accomplished purely by reducing the current. Assuming that the power factor is unaltered, the total losses must also be reduced in the same ratio; and calling the two currents I_1 and I_2 we have :—

$$\frac{I_1}{I_2} = m = \frac{c_1 I_1^2 + c_2 E^2 + c_3}{c_1 I_2^2 + c_2 E^2 + c_3} = \frac{c_1 I_1^2 + (1/n)(c_1 I_1^2)}{(1/m^2)(c_1 I_1^2) + (1/n)(c_1 I_1^2)}$$

$$\text{or } m = \frac{1 + (1/n)}{(1/m^2) + (1/n)} = \frac{n+1}{n} \times \frac{m^2 n}{n + m^2} = \frac{m^2(n+1)}{n + m^2}$$

$$\text{or} \quad m(n+1) = n + m^2 \quad \text{or} \quad (m-1)(m-n) = 0$$

$$\text{whence} \qquad m = 1 \quad \text{or} \quad m = n$$

The meaning of the above is that either $m = 1$ (no reduction at all) or $m = n$, i.e. the output can be reduced in the ratio which the current loss bears to the sum of the other two losses. If reduced by a greater amount than this the efficiency will be lower, whilst if reduced by a less amount the efficiency will be higher than at full load. Thus in a squirrel-cage induction motor the copper losses at full load are frequently about $1\frac{1}{3}$ times the sum of the iron and frictional losses, and such a machine can be run at $1/1 \cdot 33 = 75$ per cent of full-load current without loss of efficiency. The maximum efficiency will then occur at about $87 \cdot 5$ per cent of full load and will be slightly greater than the full-load efficiency.

Exactly the same formula would apply if the losses proportional to E^2 were n times the current and frictional losses, and in this case the machine would have to be under-run by reducing the pressure while keeping the current constant. Unfortunately, in a d.c. machine this would generally be inadmissible on account of commutation.*

* No mention has been made of the case in which the indices a and b are not each equal to 2. The likelihood of this occurring is hardly sufficient to justify a detailed calculation, but in general terms it will be obvious that where the index of the variable being reduced is greater than 2, the efficiency on under-running will be better maintained than it otherwise would have been, and *vice versa*.

If neither of the variable losses exceeds the sum of the other two, no under-running will be possible without loss of efficiency. In such a case it will be well to see what mode of under-running gives the least fall in efficiency. Putting the efficiency at full load $\eta = 1 - (c_1 I^2 + c_2 E^2 + c_3)/(EI \cos \phi)$, where I and E are the full-load line current and pressure, let I be reduced in the ratio $1/n$ and E in the ratio $1/m$, where n and m are variables but nm = constant, c, the known degree of under-running. Then the new efficiency becomes

$$\eta = 1 - \frac{c_1 \left(\frac{I}{n}\right)^2 + c_2 \left(\frac{E}{m}\right)^2 + c_3}{\frac{E}{m} \times \frac{I}{n} \cos \phi}$$

and putting $nm = c$ or $m = \frac{c}{n}$ we get

$$\eta = 1 - \frac{c_1 I^2 n^{-2} + c_2 E^2 (n/c)^2 + c_3}{(EI/c) \cos \phi}$$
$$= 1 - \frac{c}{EI \cos \phi} \left\{ c_1 I^2 n^{-2} + \frac{c_2 E^2 n^2}{c^2} + c_3 \right\}$$

Assuming that $\cos \phi$ is unaffected by the under-running, this can be differentiated with respect to n, giving

$$\frac{d\eta}{dn} = 0 - \frac{c}{EI \cos \phi} \left\{ -2c_1 I^2 n^{-3} + \frac{2c_2}{c^2} E^2 n + 0 \right\}$$

$$\text{This is zero when} \quad \frac{c_1 I^2}{n^3} = \frac{c_2 E^2 n}{c^2} \quad \text{or} \quad n^4 = c^2 \frac{c_1 I^2}{c_2 E^2}$$

$$\text{And as } n = \frac{c}{m}, \quad m^4 = c^2 \frac{c_2 E^2}{c_1 I^2} \quad \text{and} \quad \frac{n}{m} = \sqrt{\left(\frac{c_1 E^2}{c_2 I^2}\right)}$$

Hence the best ratio of current reduction to pressure reduction is the square root of the ratio (full-load current losses)/(full-load pressure losses).

(5) Method of Economic Calculation.

Before proceeding further, it will be well to consider the bearing of the foregoing on the economic question, i.e. the question of paying more for a machine than is physically necessary, in order to obtain a higher efficiency. There are two distinct ways of increasing the efficiency of a machine of any particular output, which may be called the qualitative way and the quantitative way. The former consists in employing the same size of frame but using higher-grade steel and better insulation, thus giving lower iron losses, a higher space-factor and therefore more copper and less copper losses. The quantitative method of improvement consists in employing a larger frame and therefore more iron and copper, thus decreasing the flux and current densities and therefore the losses.

The latter method of efficiency improvement is less sure than the former, since the larger frame will involve slightly more frictional loss, which may nullify some of the gain. It has, however, two advantages, the first of which is that any individual purchaser, knowing his own requirements but having no influence with the manufacturers, may practise it and select the machine

size which is most suitable for his particular conditions. The second advantage is that it involves no departure from standards, either in quotation or manufacture, so that it is possible to make a general survey of the advantages of economic choice, ranging over a large number of possible alternatives, without any information beyond that supplied by the makers' price list.

The quantitative method of improving the efficiency, by under-running a larger frame, has therefore been made the basis of this paper—which has so far been devoted to a general consideration of the efficiency question. It must, however, be understood that the quantitative method usually puts the worst side of the case for economic choice, and that where this method indicates an advantage to be gained from under-running, there will usually be a much greater advantage in qualitative improvements wherever these are commercially practicable.

Bearing this in mind it will be assumed that in all the cases considered and within the range of under-running proposed (usually not to a greater extent than down to 75 or 50 per cent of the rated output) the full-load efficiency can be maintained intact. It has been seen that this is true of static machines and of machines having small friction or large iron or copper losses, provided the under-running is suitably proportioned. It is not true of other machines, but as the paper is intended to explore the general possibility of economic choice, it can generally be assumed that (especially where qualitative improvement is possible) an effect at least as good as that implied in the above assumption can always be obtained for the same or less cost.

A further advantage of the method here employed is that, in reference to quality, only one or two changes are possible with any given frame, so that the range of choice in this direction is definitely limited. Problems involving this kind of action therefore usually consist in the choice between two or three specific alternatives. In this paper, on the other hand, a method is indicated whereby the general effect of efficiency-increases over a large range of possibilities can be investigated, and the exact point found up to which they can profitably be carried in any particular case.

Since economic choice and physical choice are quite unconnected, it is essential to consider each of these separately, and for this purpose any particular size of frame will be regarded as something having a definite efficiency whatever the load on which it is used, and, for the time being, physical limits will be entirely neglected. The general lines of such an economic calculation were indicated in the author's paper in the *Journal* (vol. 62, p. 901) and consist in deciding on a basis of comparison and then summing on this basis all the costs likely to be affected by the change in question.

Taking as a basis annual costs or "charges," it will be assumed that when a large frame is installed instead of a small one the only increase in cost is the annual interest and depreciation on the larger machine, and the only decrease is the lessened cost of the machine losses. These two varying charges can be regarded as the dependent variables in the problem, one of which increases and the other decreases with an increase in the independent variable (the frame size). Graphically, the last-mentioned forms the base on which two curves can be plotted whose sum will indicate the position of minimum cost or economic frame size. This base could therefore be scaled in frame dimensions, maximum output, or other suitable unit, and in the author's previous paper several different scales were experimented with. But as a basis for a general consideration of all types, machine first cost is found to be the most suitable unit, and this has therefore been adopted throughout this paper.

In what follows, the first cost is denoted by F and the combined rate for interest plus depreciation by r. (If the machine has a salvage value at the end of its useful life, r must be adjusted in the manner explained in the previous paper, and if other items, such as insurance, are affected by the choice of frame size, these may also be included in r). The total capital charges which are relevant to the choice in question are then represented by Fr, i.e. this is the annual cost of owning this particular machine instead of any other.

The other item of cost which will vary in the problem is the cost of the energy wasted in machine losses, which will be inversely dependent upon the efficiency. The best way of expressing the efficiency from this point of view is by means of the ratio, losses/output, which has already been referred to as the loss ratio. In the calculations which follow, the losses will be in watts and the output in horse-power or kVA. (This makes the calculations more convenient, and avoids unduly low values and the appearance of a large number of cyphers in the rate-of-change expression.) The loss ratio, denoted by Q, will therefore be found from $[(1/\eta) - 1)] \times 746$ in the case of the motors and $[(1/\eta) - 1] \times 1\,000$ in the case of transformers.

The importance of the quantity Q lies in the fact that, for any structure having this efficiency, the losses at any particular load can be obtained by simply multiplying Q by the load. The cost of the energy usefully converted in the machine is thus omitted from the problem, and the cost of the energy wasted is given by $Q \times$ horse-power output $\times$ hours of service per annum $\times$ cost (£) of energy per kWh divided by 1 000. Moreover, the last three items are constant relative to the frame size, and are mutually replaceable in the sense that, for example, 40 h.p. for 8 hours a day is just the same economically as 80 h.p. for 4 hours. It is therefore well to have a composite term for the product of these three, and calling this product the Power-Service-Price (P.S.P.),* the loss charge becomes $Q \times \frac{\text{P.S.P.}}{1\,000}$(£).

Hence, omitting all those items which are unaffected by the choice of frame size, it will be seen that the total annual expenses involved in obtaining the required service can be expressed as the sum of the capital and loss charges $Fr + Q \times \frac{\text{P.S.P.}}{1\,000}$. If these two are plotted to a base of F, the former will be a straight line rising with F, whilst the latter will fall as F increases, since the efficiency is greater, and therefore the loss (for a given horse-power) less, the greater the expenditure on frame

* Thus for a 10-h.p. motor running for 8 hours a day, 300 days a year, with energy at 1d. a unit the P.S.P. would be $(10 \times 8 \times 300)/240 = 100$ and the same figure would cover 10 h.p. for 24 hours a day with energy at $\frac{1}{3}$d. or 40 h.p. for 4 hours a day with energy at $\frac{1}{2}$d.

cost (cf. Fig. 1). The sum of the two will indicate the point of minimum cost and therefore the most economical size of frame to employ.

The only objection to this method of calculation is that it has to be repeated not only for every different horse-power but for every change in the conditions of service. In order to avoid such a recalculation and to establish a general method of solution for any machine of this type and speed, the total charge expressed above can be differentiated with respect to F, giving a rate of change $r + (\text{P.S.P.}/1\,000) \times dQ/dF$ which must be zero at the point where the total charge is a minimum.

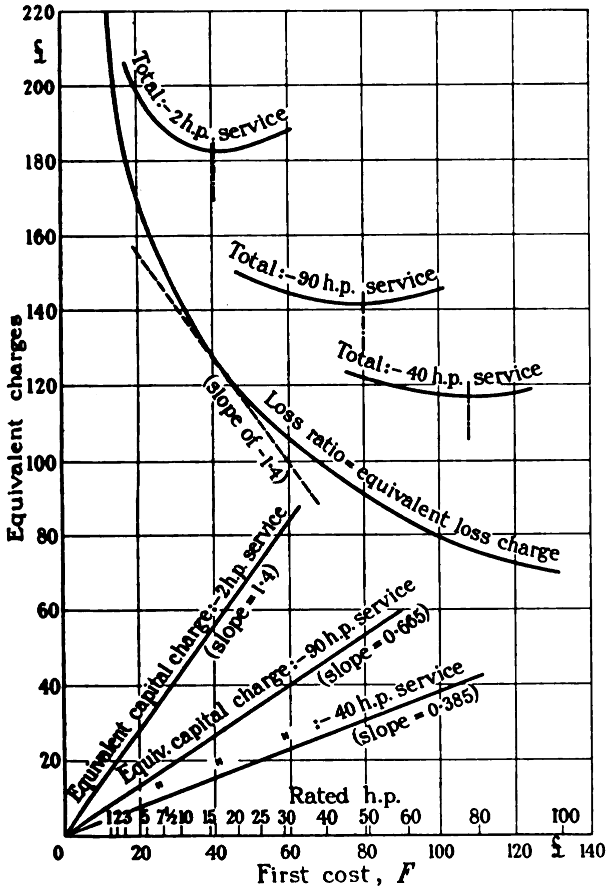

Fig. 1.—Squirrel-cage motor costs.

Hence at this point $dQ/dF = -1\,000\,r/\text{P.S.P.}$, or if the interest and depreciation are expressed per cent (r'), $dQ/dF = -10r'$ P.S.P. By finding the value of dQ/dF for a complete range of machines of the type concerned it is possible to use this to determine the most economical frame size for any power and conditions of service whatsoever.

(6) Application to Induction Motors.

The first type of machine to be considered is that of a squirrel-cage induction motor running at 1 000 r.p.m. (synchronous) on a 50-period supply. Columns 2 and 3 in Table 1 give the first cost and the full-load efficiencies for a range of frames rated at 1 to 100 h.p. at this speed, the actual figures being averaged from quotations of five or six different makers. Col. 4 gives the loss ratio, calculated from $(1/\eta - 1) \times 746$.

In order to find the rate of change of this quantity with respect to F, it can either be plotted to this base on a large scale and the slope determined graphically, or else an empirical formula can be developed and then differentiated.* Both of these methods were tried in this instance and gave results fairly similar over most of the range, but appreciably different at the lower extreme. In any actual problem, of course, the choice would only range over a comparatively few sizes, and it is probable that either the graphical or the algebraic differentiation would give equally satisfactory results. Using the graphical figures, col. 5 gives the values of dQ/dF for each value of F which corresponds to an actual frame size.

In order to illustrate the use of the above figures, three examples may be given, differing as much as possible in their data. Tabulating first the data, and then the calculations therefrom, these are shown in Table 2.

It will be noted that in not one of the above cases can the correct frame size to employ be said to be definitely specified by the results of the economic calculation. In the first case, with continuous running and relatively dear energy, the economical size is enormously bigger than that determined by heating considerations, namely 15 h.p. for an output of 2 h.p. Naturally, so big a frame as the 15 h.p. size would lose its efficiency if under-run to anything like this extent, but the economic calculation is sufficient to show that for this service a very much larger size than the 2 h.p. frame would be justified. For the 40 h.p. service also an appreciably larger size is indicated, probably 60, 70 or 80 h.p. rating, depending upon the alternatives actually available and the proportions of the losses (see later). In the case of the 90 h.p. service, owing to the small number of hours a day and the cheapness of the energy, combined with the high rate of interest, the economical size is smaller than that based on the ordinary heating rating, and the latter must therefore be chosen.

The above cases are illustrated graphically in Fig. 1. The base of this graph is the first cost F plotted to an even scale (£), and on this base are also shown the rated horse-powers of the frames obtainable at these prices. The reciprocals of the efficiencies obtainable with these frames are represented by the falling curve labelled "loss ratio," the ordinates being scaled to show $(1/\eta - 1) \times 746$. For any particular service the loss charge (£) would therefore be obtained from this curve by multiplying by P.S.P./1 000. On the same base the capital charge Fr will be a straight line through the origin, and in any given instance the two curves can be added, to see where the total becomes a minimum.

To avoid redrawing for each particular case, the ordinates can all be divided by P.S.P./1 000, the values then being termed "equivalent charges" (see Fig. 1). The loss curve is then fixed for every condition of service, and the capital curve plots Fr divided by

* By taking logarithms of Q and F and plotting them, a very close approximation to a straight line was obtained over the above range. The empirical law thus established was $Q = (F)^{-0{\cdot}48}$, whence $dQ/dF = -0{\cdot}48(F)^{-1{\cdot}48}$.

$\text{P.S.P.}/1\,000 = \dfrac{1\,000Fr}{\text{P.S.P.}}$ which will still be a straight line through the origin, its inclination varying with every change in the conditions of service and the prices of energy and capital. In the three cases listed above, its inclination will be given by arc tan 1·4, 0·385 and 0·665 respectively, and these lines are labelled "equivalent capital charges." Adding these to the loss curve gives the three totals shown, and thus indicates the frame position for minimum total cost in each case. Another way is to reverse the capital curve and bring it up to the loss curve so as to show at what point it is tangential (see dotted line, representing slope of − 1·4).

In a similar manner any other power, hours of service, or price of energy or capital, can be resolved into a factor which will at once show the economical size of frame on the assumptions made above. If the frame thus specified is not more than, say, 50 per cent larger than the size determined by the heating limit, and if there is no possibility of qualitative selection, this size may be chosen without further calculation, care being taken to purchase a higher-voltage machine so that it

TABLE 1.

Squirrel-Cage Induction Motors.

Column 1 Rated Output	Column 2 First cost, F	Column 3 Rated full-load efficiency	Column 4 Loss ratio, Q	Column 5 $-\dfrac{dQ}{dF}$	Column 6 At 5 % interest And with life of	Column 7 Economical service-price	Column 8 $\left(\dfrac{1}{\text{efficiency}}-1\right) \times \sqrt[3]{\text{h.p.}}$
h.p.	£ s.	per cent			years		
1	12 18	77·0	223	12	15	7·6	0·30
2	14 10	78·7	202	9·5	16	4·6	0·34
3	16 4	80·0	186	6·3	17	4·5	0·36
5	22 4	82·0	164	2·95	18	5·6	0·37
7½	26 16	83·3	150	2·34	18	4·7	0·39
10	31 10	84·0	144	1·87	19	4·2	0·41
15	39 5	85·3	129	1·43	19	3·7	0·42
20	46 4	86·0	121	1·18	20	3·3	0·44
25	52 16	87·0	111	1·00	20	3·1	0·43
30	58 16	87·5	107	0·92	20	2·8	0·44
40	69 18	88·5	97	0·76	20	2·5	0·44
50	81 5	89·0	92	0·66	20	2·3	0·45
60	92 0	90·0	83	0·57	20	2·3	0·43
80	110 10	91·0	74	0·36	20	2·7	0·43
100	132 12	91·5	69	0·30	20	2·6	0·43

TABLE 2.

	Case 1	Case 2	Case 3
Horse-power required at 1 000 r.p.m.	2	40	90
Average hours per day during which the above horse-power is required	24	8	4
Days per year	365	300	300
Price of energy per kWh	1d.	½d.	½d.
Power-Service-Price (P.S.P.)	73	200	150
Estimated life (years)	16	20	20
Estimated salvage value	Zero	10 % of 1st cost	10 % of 1st cost
Rate of interest on capital	6½ %	5 %	8 %
Combined rate per cent (r') of interest and depreciation	10·24 %	7·7 %	9·97 %
Value of $10r'$/P.S.P.	1·40	0·385	0·665
(Which must equal the value of the slope dQ/dF at the most economical point)			
Rated h.p. of frame nearest to this point	15	80	50

may be under-run as regards pressure as well as regards current. If the economical size indicated is very considerably above the heating rating, further consideration must be given in view of the loss in efficiency occasioned by substantial under-running.

Thus in Case 2 given above (40 h.p. service) probably the best standard frame that could be chosen would be the 60 h.p. size, which would then be under-run in the ratio 1·5 to 1. Assuming that the full-load current and pressure losses are in the ratio of 2 : 1, the most economical pressure reduction will be in the ratio $\sqrt{\frac{1\cdot5}{\sqrt{2}}} = 1\cdot03$ and the current reduction will be $\sqrt{2}$ times this, or 1·46, making a total power reduction of $1\cdot03 \times 1\cdot46 = 1\cdot5$. Hence if the supply pressure is 400 volts, the 60 h.p. machine can be ordered for, say, 412 volts, and when under-run to give 40 h.p. at the

$2\frac{1}{2}$ on the larger, and such values can only be described as extraordinarily small. They mean that a large squirrel-cage induction motor giving its full rated output for 8 hours a day and 300 days a year is only economical when energy costs ½d. or less per kWh. With energy at the usual prices the most economical frame would be much bigger, whilst if the motor were required for day and night service it might be economical to have it 2 or 3 times as big.*

(7) Application to Small D.C. Motors.

The next case to be considered is that of d.c. shunt motors running at 1 000 r.p.m. and ranging from ¼ h.p. to 15 h.p. in size. The first cost and full-load efficiencies for such a range, averaged from a number of different quotations, were tabulated in the author's previous paper, and it is here proposed to apply the more general

Table 3.

Small D.C. Motors.

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
					At 5 % interest		
Rated output	First cost, F	Rated full-load efficiency,	Loss ratio, Q	$-\frac{dQ}{dF}$	And with life of	Economical service-price	$\left(\frac{1}{\text{efficiency}}-1\right) \times \sqrt[3]{\text{h.p.}}$
h.p.	£ s.	per cent			years		
¼	7 15	61·0	477	70	12	4·4	0·40
½	10 7	66·7	373	28·3	13	5·4	0·39
¾	12 4	70·2	317	19·4	14	5·3	0·38
1	14 8	71·8	291	14·9	15	5·2	0·39
1·5	17 10	75·7	239	9·0	16	5·7	0·37
2	20 0	77·0	223	6·25	16	6·1	0·38
3	26 8	78·6	203	4·1	17	6·2	0·39
4	29 10	79·9	188	3·6	17	5·3	0·40
5	32 7	80·9	176	3·0	18	5·2	0·40
7·5	37 4	82·4	159	2·2	18	4·6	0·41
10	44 16	83·6	147	1·2	19	6·4	0·42
12·5	50 0	84·0	142	0·75	19	8·2	0·44
15	57 8	84·2	140	0·38	20	—	0·46

lower pressure it will be found to have an efficiency of 89·8 per cent. The annual cost for capital and losses will then be £24 as against a figure of £24 16s. for the 40 h.p. frame run at its full output; and this is apart from any incidental gain such as longer life or greater overload capacity.

Referring again to Table 1, it is interesting to see whether the advantage of under-running is the same for all sizes. In order to make the values in col. 5 mutually comparable, a set of figures has therefore been worked out for lives of 15 to 20 years (col. 6) with interest at 5 per cent and salvage value 10 per cent of first cost. These figures (col. 7) give the value of $(dF/dQ) \times (1\,000\,r/\text{Rated h.p.})$ and hence show the service-price * at which each frame can economically be used to give its normal rated horse-power. It will be seen that the figures decline roughly from 5 on the smaller sizes to

method of the present paper to the same set of figures. Cols. 1, 2 and 3 in Table 3 give these figures, and col. 4 gives the ratio Q = (loss in watts)/(output in h.p.), this being obtained from $(1/\eta - 1) \times 746$. By graphical differentiation the value dQ/dF was found for each frame size and is shown in col. 5.

This value, as before, is the key to the economic solution, and from it the most advantageous size can be estimated for any set of prices and conditions of service. Thus, to take a single instance, suppose that the service required is 1 h.p. for 8 hours a day and 300 days a year with energy at 1d. a unit. The P.S.P. is 1 × 2 400

* The term "service-price" is used to indicate the annual hours of service multiplied by the price (£) of energy per kWh.

* It may be objected that the above rate of interest is abnormally low, but a change in this rate by no means makes a proportional change in the result, since the interest payment and depreciation deposits are oppositely affected (i.e. the full first cost is not really owing for the whole of the working life, but is gradually paid off, or balanced by interest-bearing deposits into a sinking fund). In the present case, if interest were at 8 instead of 5 per cent, the figure of 5 for the economical service-price on the small frame sizes (17-year life) would become 6·9, whilst the figure of 2·5 for the larger sizes (20-year life) would become 3·2. Hence it will be seen that, even if capital is considerably more expensive, the service-price at which these frames are economical for their rated outputs is still surprisingly small.

$\times 1/240 = 10$. Taking a life of 15 years with interest at 5 per cent and salvage value 10 per cent of first cost, the combined rate for interest plus depreciation is 7·7 per cent, or $r = 0{\cdot}077$. Hence the most economical size will be when the rate of change $dQ/dF = 1\,000\, r/\text{P.S.P.} = 7{\cdot}7$, and this will occur on a frame rated somewhere between 1½ and 2 h.p. (col. 5).

As in the previous case, a set of figures has been worked out assuming interest at 5 per cent and lives varying, in this case, from 12 to 20 years (cols. 6 and 7). These figures show that the service-price at which the machines can be economically employed on their rated outputs ranges from about 4 to 7, there being no discernible tendency for the figures to vary with the size. These are in general agreement with the figures found by a similar method in the previous paper, allowing for the fact that the graphical differentiation was carried out quite independently in the two cases. It will be noticed that the figure is about twice that for the induction motors.

(8) Application to Transformers.

The last case to be considered is that of a range of single-phase transformers running off a 50-period supply. The transformer, being a two-loss structure, conforms most exactly to the assumption previously made regarding the efficiency on under-running, and it is only necessary to reduce the pressure and current in the correct ratios in order to obtain an efficiency as great as or greater than the full-load value. The economic advantages of under-running can therefore be pronounced upon with more certainty than with any other structure except the single-loss type such as the cable; and, moreover, the occurrence of day and night running is more frequent than with the other types of apparatus considered. On the other hand, the normal efficiency being so high, there is less margin for improvement; and it will be found that the case for under-running is, in general, less strong than with a.c. and d.c. motors.

As before, the qualitative improvement of efficiency will not be touched upon, attention being confined to the quantitative method of installing a larger (standard) transformer. In Table 4 are shown the rated outputs, prices and full-load efficiencies for a range of single-phase transformers on 50 periods, and for high-tension pressures not exceeding 2 000 to 3 000 volts. In this case the figures given are those of a single manufacturer and not averaged from a number, as it was desired also to compare the iron sections and other particulars.

Table 4.

Single-Phase Transformers.

Column 1 Rated output	Column 2 First cost, F	Column 3 Rated full-load efficiency	Column 4 Loss ratio, Q	Column 5 $-\frac{dQ}{dF}$	Column 6 Economical service-price at 5 %; life 20 years	Column 7 $\left(\frac{1}{\text{efficiency}} - 1\right) \times (\text{kVA})^{0{\cdot}31}$
kVA	£ s.	per cent				
¼	6 9	90·8	101·3	17	18·2	0·065
½	7 18	92·3	83·4	13	11·9	0·067
1	8 10	93·7	67·2	10	7·7	0·067
1½	10 12	94·49	58·3	5·2	9·9	0·066
2	12 4	95·18	50·65	3·3	11·7	0·063
3	15 6	96·17	39·83	1·95	13·2	0·056
5	20 0	96·40	37·35	1·02	15·1	0·062
7½	23 10	96·93	31·68	0·66	15·6	0·059
10	27 0	97·14	29·44	0·60	12·9	0·060
15	34 0	97·26	28·50	0·49	10·5	0·066
20	39 0	97·59	24·70	0·38	10·1	0·063
25	43 6	97·76	22·90	0·33	9·3	0·062
30	48 0	97·92	21·24	0·22	11·7	0·061
40	58 6	98·06	19·78	0·13	14·8	0·063
50	67 0	98·11	19·26	0·05	30·8	0·065
60	73 12	98·15	18·87	0·045	28·5	0·068
75	89 0	98·20	18·33	0·040	25·7	0·071
100	110 0	98·30	17·29	0·036	21·4	0·073

The method followed is exactly that of the previous cases, and col. 4 shows the loss ratio Q = (losses in watts)/(rated output in kVA). Differentiating graphically with reference to F gives the ratios dQ/dF in col. 5, the values shown being those which occur at values of F corresponding to the actual frames listed. These rates of change can be utilized as before to find the most economical frame size for any set of conditions.

As an example, assume that 5 kVA is required at 50 periods, with a length of service of 20 years and a salvage value at the end of this time of 10 per cent of the first cost. In the first case let it be supposed that high prices rule, that energy costs 3d. a unit and capital 8 per cent per annum, giving a combined rate for interest and depreciation of 9·97 per cent. If the service is

required for 8 hours a day and 300 days a year, the P.S.P. will be $5 \times 8 \times 300 \times 3/240 = 150$. Hence the most economical frame size will be when dQ/dF has the value $-1\,000r/\text{P.S.P.} = -99 \cdot 7/150 = -0 \cdot 66$, which occurs at the frame rated to give 7·5 kVA.

As a contrast let it be supposed that the full-load service of 5 kVA is required day and night continuously * with energy at 0·7d. and interest at 5 per cent. For maximum economy dQ/dF must now equal $-\dfrac{77 \times 240}{5 \times 24 \times 365 \times 0 \cdot 7} = -0 \cdot 6$, which occurs at the frame capable of 10 kVA (col. 5).

Referring to this last example, if the intending purchaser, after working through to the above conclusion, wishes to follow the dictates of his economic conscience, his course will be to order a transformer of 10 kVA output and for a voltage $\sqrt{2}$ times his actual line pressure, so that if he requires 400 volts he will order approximately 565 volts. (The exact figure is not important; the one given assumes that the transformer

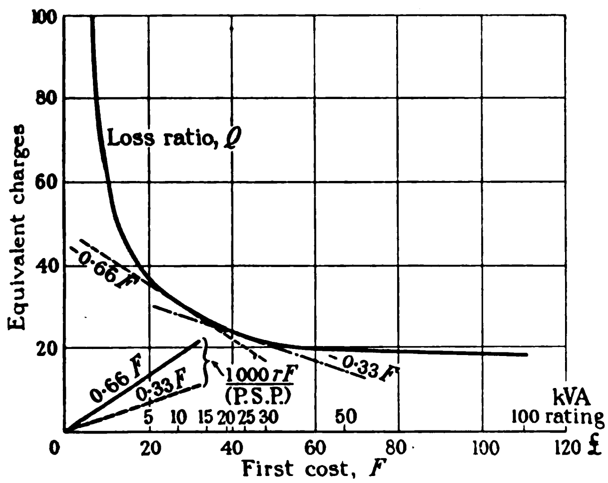

FIG. 2.—Single-phase transformer costs.

is designed to give equality of losses at full load.) When employed to give 5 kVA at 400 volts, the copper and iron will then each be under-run in the ratio $1/\sqrt{2}$ and the two losses will be approximately halved, leaving the efficiency exactly as for 10 kVA, and the total annual costs a minimum.

As in the other cases, a set of figures has been worked out with interest at 5 per cent, salvage value 10 per cent, and for a uniform life of 20 years. Working out the values $(dF/dQ) \times (1\,000r/\text{rated kVA})$ for each frame size, col. 6 gives the service-price at which each frame can be economically employed to give its actual rated output. Comparing these figures with the corresponding ones for the rotating machines, it will be noticed that the average for the transformers, namely 15, is 3 times as great as that for the small d.c. motors, and 6 times that for the a.c. machines.† Hence the advantage of under-running is notably less, and the service would have to be at full load continuously in order to present as favourable a case for economic selection as with a d.c. machine running only 8 hours a day. Another way of putting the matter is to say that, in order to establish an economic case for the installation of the next larger machine (say $1\frac{1}{3}$ times as big), the service price would have to be 20—corresponding to energy at 2d. for an 8-hour day or $\frac{2}{3}$d. for a 24-hour day.

The above can be better illustrated by means of a graph (see Fig. 2). The base of this shows first cost (£), but as regards the ordinates, no attempt has been made to scale these similarly. In fact, this graph omits the preliminary work of the previous one, and the ordinates are pure numbers, representing what may be called "equivalent charges." The falling curve plots the loss ratio Q, and the straight lines through the origin plot the values $1\,000r\ F/\text{P.S.P.}$ The steeper of the two lines represents the 5-kVA 8-hour service at 3d. a unit, and has a slope of arc tan 0·66. The reverse of this line, having a slope of −0·66, is also shown (dotted) brought up to the loss curve, and it will be seen to be tangential at the frame size rated to give 7·5 kVA. The shallower curve through the origin has a slope of just half as much and represents 10 kVA for the above-mentioned hours and price of energy. The reverse of this (chain-dotted) is tangential at the 25 kVA size and illustrates the economic point for this service.

(9) Conclusion.

Several important factors have been neglected in the above, e.g. power factor and load factor, and whilst these require fuller treatment than is possible in the present paper, one or two points may be noted here. As regards the former, the transformer efficiencies have been taken at unity power factor throughout, and, whilst this may not be the case in practice, the general relationship between the efficiencies of the different sizes is very similar whatever the power factor, provided the latter is not affected by the change in question. It is therefore doubtful whether an all-round alteration in power factor will materially affect the solutions obtained, but of course if the power factor is known it is an easy matter to use the appropriate efficiencies at this power factor throughout the calculation. With induction motors, under-running a larger machine may result in a change in power factor as well as in efficiency, and if the cost of energy includes an item for idle volt-amperes, this would have to be taken into consideration in any economic comparison.

A more serious omission is that of load factor, since it has been assumed throughout that the load taken from the plant is a constant maximum figure during the whole of the time for which it is connected. But in practice when a 40-h.p. machine is specified this is merely the maximum power required, with a mean load factor of perhaps 75 per cent, so that the economic calculations should all be based on the figure of 30 h.p. Then if 30 h.p. is the usual load and 40 h.p. merely an occasional maximum, this may be sufficiently accurate. If, however, the load varies greatly, this will not suffice, since the average all-day efficiency on a range of loads whose average is 30 h.p. cannot be found by merely computing the efficiency at a fixed load of 30 h.p.

* It is realized that this is not a likely condition (see later).

† If interest were at 8 per cent instead of 5 per cent and if all other items were unaltered, the average figure of 15 for the economical service-price would then become 20 (cf. footnote on page 345).

Hence on a varying load (since only the current loading will be varying) the required loss ratio must be calculated from the full-load pressure and frictional losses plus the R.M.S. value of the current losses divided by the mean output, and this can only be accurately determined if a load curve for the year is available. The point becomes particularly important in the case of transformers which are on full load for only a fraction of the time for which they are connected—a problem which has been considered by a number of writers on the subject of transformers. For such a case this paper cannot do more than indicate very approximately the total economic size, whilst throwing no light on the most economic proportions.

The above remarks apply with even more force to a further item which has been neglected, namely, varying costs of energy. When the cost of energy varies, the loading remaining constant, it is legitimate to take an average of the energy price over the period during which the plant is connected; but when the loading and therefore the efficiency vary simultaneously with the energy price this calculation will be inaccurate, since then the different losses will have varying degrees of importance according to the time of day at which they occur. Such a problem is considerably more complicated and it is impossible to do more than mention it here, referring to some of the authorities who have dealt with it.*

A final item which has been omitted is that of regulation. In the case of transformers this may sometimes be a determining factor, and the effect of the under-running upon the regulation will then have to be taken into consideration.

Summarizing the conclusions of this paper, it may be said that most electrical machinery can be employed at an output lower than its rated one in such a way as to give an efficiency greater than that obtainable on a smaller machine running on its full load. This fact may be made use of on economical grounds, not merely as a possible basis for action in itself, but also as a guide to the still greater advantages possible through re-designing. The method developed enables the designer or purchaser to estimate the extent to which efficiency is worth paying for, or, more strictly, the quantities of active materials which are economically justified, under any given set of conditions.

The results thus obtained show an advantage accruing to under-running a frame below its rated output in a very large number of cases with squirrel-cage motors, fewer with small d.c. motors, and still less with transformers. Speaking of the rotating machines, one can only repeat and re-emphasize a previous conclusion, that "It is not too much to suggest that such a review may lead to a complete revision of our methods of choosing motors for long-period service, future ratings being determined by economic considerations, whilst the heating properties, like the insulating properties, fix only a lower limit." *

* See particularly L. VIDMAR: *Elektrotechnik und Maschinenbau*, 1917, vol. 35, p. 232; summarized in *Science Abstracts*, 1917, vol. 20, Abstract 714.

* "The Economics of Power Consumption," *Journal I.E.E.*, 1924, vol. 62, p. 908.

FREQUENCY VARIATIONS IN THERMIONIC GENERATORS.

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SUMMARY.

The paper is divided into six parts, as follows :—

In Part I the variations of frequency which occur in mechanical oscillating systems with pendulum control are referred to. Unless the driving impulses are given at the moment the pendulum is vertical, the frequency of the oscillations varies from the true oscillation frequency of the pendulum. When the pendulum is near the limit of its swing an impulse directed inwards makes the clock go fast, whilst an impulse directed outwards makes the clock go slow. Such an effect is "reversible" because the clock goes fast or slow according to the direction in which the impulse is applied. Another type of variation is connected with the amplitude of the swing, and makes its appearance unless the amplitude is infinitesimal. Increase of amplitude always makes the clock go slow, and the effect is therefore "irreversible."

In Part II the phase relationships of currents and potentials in a thermionic generator are examined, and it is shown that the frequency of the oscillations is affected by the nature of the coupling between the grid and anode circuits. Equations are obtained which give the difference between the frequency of the oscillations generated and the resonant frequency of the tuned circuits. These equations show that the variations of frequency connected with the method of coupling are analogous to the reversible variations existing in the pendulum-controlled clock. With normal coupling the thermionic generator goes slow, with reversed coupling it goes fast, and with resistance coupling the variation disappears.

In Part III three "irreversible" variations of frequency are discussed, namely :—

(i) A variation connected with a change in the effective inductance of the circuit, which occurs when the oscillation is free instead of forced ;

(ii) A variation connected with a change in the resonant frequency of a damped circuit, which occurs when the oscillation is free instead of forced ; and

(iii) A variation associated with the presence of harmonics in the E.M.F. generated by the valve.

In Part IV certain points in the design of thermionic generators employing resistance coupling are discussed.

In Part V the design of thermionic generators using reversed coupling is discussed, and some interesting points affecting the design of untuned circuits are described.

In Part VI the experimental results obtained with various types of circuit are given, and are explained in terms of the theoretical variations discussed in Parts II and III.

The characteristics of various types of constant-frequency generator are then compared. It is pointed out that frequency variations associated with changes in the voltage of supply can be reduced below 1 part in 20 000, or 1 part in 50 000, according to circumstances.

PART I.

SOME PROPERTIES OF MECHANICAL OSCILLATING SYSTEMS.

Electrical oscillating systems driven by thermionic valves, and mechanical oscillating systems controlled by pendulums or balance wheels, have many properties in common. It is proposed to refer briefly to certain well-known properties of the mechanical systems, as the discussion will be found helpful in dealing with the purely electrical problems.

The problem of designing a standard clock involves many points of interest, but the first and most fundamental horological principle is that the impulse must be given to the pendulum at or near its zero (vertical) position. The reason for this rule may be briefly stated as follows :—

For small amplitudes the time T taken by the pen-

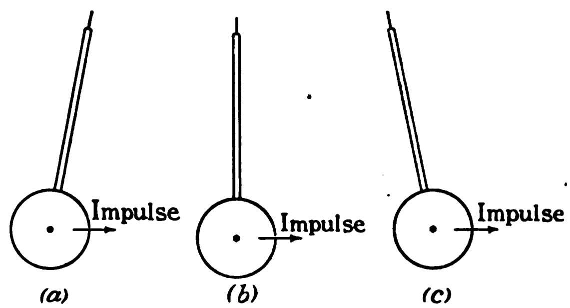

FIG. 1.

dulum to describe a complete oscillation is given by the equation

$$T = 2\pi\sqrt{\frac{l}{g}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where l is the length of the pendulum.

If the pendulum is subject to damping, the friction will assist gravity when the pendulum is swinging outwards, and the time of the quarter oscillation will be shortened from $\frac{1}{4}T$ to, say, $\frac{1}{4}T - \tau$. During the inward swing the friction will oppose gravity, and the time will be lengthened from $\frac{1}{4}T$ to $\frac{1}{4}T + \tau$, the total time taken for the complete oscillation being sensibly unaltered.

When the loss of energy due to damping is made good by sudden impulses—as is usually the case in mechanical systems—the moment at which the impulse is given is of vital importance. There are three cases (see Fig. 1), as follows :—

(*a*) *When the impulses are imparted to the pendulum*

at the end of its swing and are directed inwards. In this case the frequency of the oscillations is greater than the natural frequency of the pendulum, the amount of the difference depending on the strength of the impulses. Increasing the strength of the impulses increases the variation and makes the clock go fast.

(*b*) *When the impulses are given at the moment the pendulum is vertical.* In this case the frequency of the oscillations is the natural frequency of the pendulum.

(*c*) *When the impulses are imparted to the pendulum at the end of its swing and are directed outwards.* In this case the frequency of the oscillations is less than the natural frequency of the pendulum, the amount of the difference depending on the strength of the impulses. Increasing the strength of the impulses increases the variation and makes the clock go slow.

When the oscillations have settled down into a steady state, the energy supplied by the impulses must equal the energy lost by the damping. Increased strength of impulse and increased damping are therefore synonymous.

The type of frequency variation which occurs when the impulses are not given to the pendulum in its vertical position may, for obvious reasons, be described as "reversible."

Before leaving the question of the clock another type of variation must be referred to. For very small amplitudes the time of swing is independent of the amplitude. When the arc swept out is not very small, however, the frequency varies slightly with the amplitude, an increase of amplitude causing a reduction of frequency. If the impulses are increased in strength therefore the clock will go slow, even if the impulses are given at the correct instant. This effect has been analysed in mathematical textbooks and need not be dealt with in detail here.

This second type of frequency variation is "irreversible." A stronger impulse can only make the clock go slow and cannot make it go fast.

It is interesting to note that in Fig. 1 (*a*) the two types of variation are in opposite senses and tend to neutralize one another.

In electrical oscillating systems the energy is not usually supplied by means of a short impulse, but is spread over at least half of the complete period. The underlying principle is, however, the same. An impulse proportional to cos θ will leave the period of oscillation sensibly constant, whereas an impulse proportional to sin θ will increase or diminish the period of oscillation according to the direction in which it is applied.

PART II.

FREQUENCY VARIATIONS DUE TO CHANGES IN ANODE RESISTANCE.

TYPES OF COUPLING.

All thermionic generators employ some form of coupling between the grid and anode circuits of the valve.

Stray capacity is inherent in all electrical circuits, and stray capacity coupling invariably exists between the grid and anode circuits of a thermionic valve. Owing to the fact that the filament is common to both grid and anode circuits, capacity coupling can have only one sense, and this type of coupling is conveniently described as *normal coupling.*

Inductive coupling may be in either direction, and inductive coupling which assists the capacity coupling is defined as normal coupling. Circuits which generate oscillations by means of normal coupling may be described as *orthodyne circuits.*

Inductive coupling which opposes the capacity coupling is described as *reversed coupling,* and circuits which generate oscillations by means of reversed coupling may be described as *antidyne circuits.*

Oscillations may be generated by means of either normal or reversed coupling, the only difference being that a stronger inductive coupling is required in the latter case than in the former.

Oscillations may also be generated by means of a resistance coupling between the grid and anode oscillatory circuits, and this type of coupling will be described in due course. Circuits generating oscillations by means of resistance coupling may be described as *rheodyne circuits.*

THERMIONIC GENERATOR WITH INDUCTIVE COUPLING.

The formulæ used in this discussion are explained in detail in the Appendix.

Fig. 2 shows a type of circuit commonly used for generating oscillations, and Fig. 3 shows the "equivalent network."

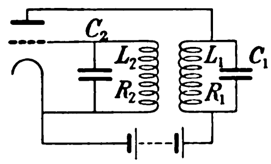

FIG. 2.

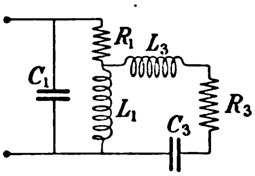

FIG. 3.

The values of L_3, R_3, C_3 are

$$L_3 = (L_1^2/M^2)L_2\sigma$$
$$R_3 = (L_1^2/M^2)R_2$$
$$C_3 = (M^2/L_1^2)C_2$$

where M is the mutual inductance and $\sigma = 1 - (M^2/L_1L_2)$.

The problem can be simplified by assuming that the energy absorbed in the grid circuit is negligible compared with the energy absorbed by the anode circuit, so that the flow of current in $L_3R_3C_3$ can be ignored in dealing with the circuit $L_1R_1C_1$.

The difference in phase between the E.M.F. across L_1 and the E.M.F. generated in the valve is given by the equation

$$\tan\phi = \frac{-2Ay + R_1}{\sqrt{(L_1/C_1)} + AR_1\sqrt{(C_1/L_1)}} \quad . \quad . \quad (2)$$

where ϕ is an angle between $-90°$ and $90°$.

In the special case in which there is no grid current, $\tan\phi = 0$ and $y = R_1/2A$, so that

$$\omega = \frac{1}{\sqrt{(L_1C_1)}}\left\{1 + \frac{R_1}{2A}\right\} \quad . \quad . \quad . \quad (3)$$

an equation which will be found in slightly different form in the textbooks.

The term R_1 is usually small compared with $2Ay$ and, for the moment, it will be regarded as negligible in the numerator of equation (2).

The circuit $L_3\,R_3\,C_3$ is an acceptor circuit, and the difference in phase between the potential across C_3 and the potential applied to the circuit is given by the equation

$$\tan\theta = \frac{R_3\sqrt{C_3}}{2x\sqrt{L_3}} = \frac{R_2\sqrt{C_2}}{2x\sqrt{(L_2\sigma)}} \quad . \quad . \quad . \quad (4)$$

Finally, the difference in phase between the potential across C_3 and the E.M.F. generated in the valve is $(\theta + \phi)$, where ϕ and θ are defined by equations (2) and (4) above.

Now the E.M.F. generated in the valve differs in phase by 180° from the variations in the potential of the grid, and this in turn is the potential across C_3. Actually the difference in phase between the potential across C_3 and the E.M.F. generated in the valve may be 0° or 180°, according to the direction of the coupling between the coils.

Therefore $\quad \tan\theta + \tan\phi = 0 \quad . \quad . \quad . \quad . \quad (5)$

and

$$xy = \frac{R_2\sqrt{(C_1C_2)}\{(L_1/C_1) + AR_1\}}{4A\sqrt{(L_1L_2\sigma)}} \quad . \quad . \quad (6)$$

The quantities on the right of this equation are essentially positive, and therefore x and y must either be both positive or both negative.

If the circuits are adjusted so that $L_1C_1 = L_3C_3$, then

$$x = y = \pm\sqrt{\left[\frac{R_2C_2}{4AC_1} + \frac{R_1R_2C_2}{4L_1}\right]} \quad . \quad . \quad (7)$$

so that

$$\omega = \frac{1}{\sqrt{(L_1C_1)}}\left\{1 \pm \sqrt{\left[\frac{R_2C_2}{4AC_1} + \frac{R_1R_2C_2}{4L_1}\right]}\right\} \quad . \quad (8)$$

The sign $\pm$ depends on the direction of the coupling. With normal coupling the negative sign must be taken, and with reversed coupling the positive sign.

Those who are interested in this question of phase relationship in thermionic generators will find a number of diagrams in a paper * by D. C. Prince.

Thermionic Generator with Capacity Coupling.

Fig. 4 shows a thermionic generator with capacity coupling, the coupling due to stray capacity being of

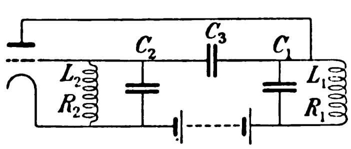

Fig. 4.—Thermionic generator with capacity coupling.

this type. To simplify the problem assume that the coupling capacity C_3 is small compared with C_1 and C_2, so that the energy taken by the grid circuit is small compared with the energy expended in the anode circuit.

The circuit L_1C_1 is a rejector circuit, and the phase of the potential across this circuit is related to the E.M.F. generated in the valve by the equation

$$\tan\phi = \frac{-\,2Ay\sqrt{(L_1C_1)}}{(L_1/C_1) + AR_1} \quad . \quad . \quad . \quad (9)$$

where ϕ is an angle between $-$ 90° and $+$ 90°.

Noting that C_3 is small compared with the impedance of the circuit $L_2R_2C_2$ it follows that the current flowing in C_3 is determined by the value of C_3 itself. The difference in phase between current and potential is therefore 90°, or nearly so.

Next consider the rejector circuit L_2C_2. The potential across the circuit is related to the current by the equation

$$\tan\theta = \frac{-\,2x\sqrt{L_2}}{R_2\sqrt{C_2}} \quad . \quad . \quad . \quad . \quad (10)$$

Finally, the potential on the grid, which is the potential across this circuit, differs in phase from the E.M.F. generated in the valve by the angle $(\phi + 90° + \theta)$.

But the potential on the grid differs from the E.M.F. generated in the valve by 180°, so that

$$\phi + 90° + \theta = 180° \quad . \quad . \quad . \quad (11)$$

$$\therefore\ \tan\phi = 1/\tan\theta \quad . \quad . \quad . \quad . \quad (12)$$

$$\therefore\ xy = \frac{R_2\sqrt{(C_2)}\{(L_1/C_1) + AR_1\}}{4A\sqrt{(L_1L_2C_1)}} \quad . \quad . \quad (13)$$

Since the various quantities on the right of this equation are positive it follows that x and y must be of the same sign. Equation (11) further tells us that θ and ϕ must be between 0° and 90°, so that x and y must both be negative.

If the circuits are so adjusted that $L_1C_1 = L_2C_2$

then

$$x = y = -\sqrt{\left[\frac{R_2C_2}{4AC_1} + \frac{R_1R_2C_2}{4L_1}\right]} \quad . \quad (14)$$

so that

$$\omega = \frac{1}{\sqrt{(L_1C_1)}}\left\{1 - \sqrt{\left[\frac{R_2C_2}{4AC_1} + \frac{R_1R_2C_2}{4L_1}\right]}\right\} \quad (15)$$

Thermionic Generator with Resistance Coupling.

This type of circuit is shown in Fig. 5. When the tuned anode and grid circuits are so adjusted that $L_1C_1 = L_2C_2$, it is clear that the E.M.F. generated by

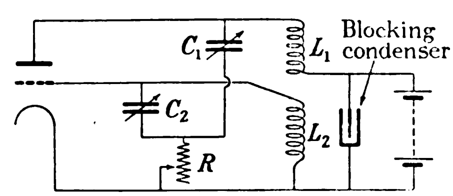

Fig. 5.—Thermionic generator with resistance coupling between the oscillatory circuits.

the valve, the potential across the anode oscillatory circuit and the potential across the coupling resistance are all in the same phase (or nearly so). It is also clear that the potential applied to the grid will differ by 180° from the E.M.F. generated in the valve.

It follows that the frequency of the oscillations generated is determined by the values of L and C and

* *Proceedings of the Institute of Radio Engineers*, 1923, vol. 11, pp. 275 and 399.

is independent of the magnitude of the various resistances.

Effect of Changes in Anode and Filament Potential.

In the case of generators with capacity coupling, it has been shown that the frequency of the oscillations is expressed by an equation of the form

$$f = \frac{1}{2\pi\sqrt{(LC)}}[1 - \sqrt{\{H + (K/A)\}}] \quad . \quad (16)$$

where A is the anode resistance of the valve and H and K are quantities depending on the fixed electrical characteristics of the circuits. It is clear from this

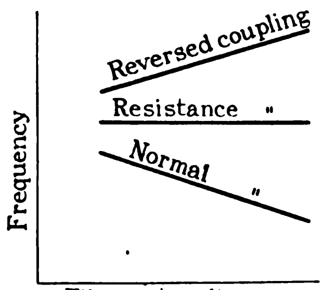

Fig. 6.—Variation of the first type.

equation that an increase in the anode resistance of the valve involves an increase of frequency, and vice versa. Normal inductive coupling produces similar results.

With reversed inductive coupling the frequency equation takes the form

$$f = \frac{1}{2\pi\sqrt{(LC)}}[1 + \sqrt{\{H + (K/A)\}}] \quad . \quad (17)$$

and the effect of changes in anode resistance is reversed.

An increase in the voltage applied to the filament of a valve increases the emission and the anode resistance

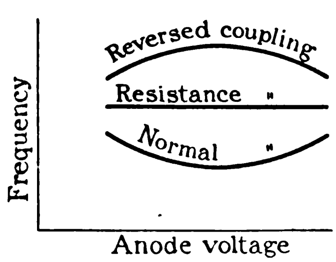

Fig. 7.—Variation of the first type.

is reduced. Changes in filament voltage would therefore be expected to give the results indicated in Fig. 6.

Changes in the anode voltage also cause variations in the anode resistance of the valve, and in any particular case there is a particular anode voltage for which the anode resistance is a minimum. Changes in anode voltage would therefore be expected to give the results indicated in Fig. 7.

The frequency variations which are associated with changes in the anode resistance of the valve are "reversible," and are analogous to the reversible frequency variations already described in reference to the oscillations of the pendulum.

With both types of oscillating system there are three cases depending on whether the impulses are in advance of the oscillations, in synchronism with them, or behind them. It is convenient to describe this kind of frequency variation as a frequency variation of the *first type*.

Frequency-Changes produced by Given Changes in Anode Resistance.

Before comparing different circuits it is desirable to define a quantity which can be used as a standard of comparison. The various equations in the previous sections determined the difference between the frequency of the oscillations generated, which was denoted by f, and the resonant frequency of the tuned circuits, which may be denoted by f_0, and the quantity x was so defined that it is a fraction satisfying the equation

$$x = (f - f_0)/f_0$$
$$\therefore \delta x = \delta f/f_0$$

It is convenient to express changes in anode resistance in a similar manner, as a proportion of the total anode resistance, and the quantity z is introduced by the equation

$$z = \frac{\delta f/f_0}{\delta A/A} = \frac{A\delta x}{\delta A} \quad . \; . \; .$$

The value of z for a generator employing two tuned circuits is found by differentiating equation (7). This gives

$$z = \mp \tfrac{1}{2}\left\{\frac{R_2C_2}{AC_1}\right\}^{\frac{1}{2}}\left\{1 + \frac{R_1AC_1}{L_1}\right\}^{-\frac{1}{2}} \quad . \quad (18)$$

At this point it may be observed that R_2, the damping of the grid circuit, consists really of two parts—a fixed part which may be denoted by R_4, and a part depending on the grid current, which can be shown to be equal to L_2/C_2G, where G is the grid resistance of the valve. The complete formula should therefore be written

$$z = \mp \tfrac{1}{2}\left\{\frac{R_4C_2}{AC_1} + \frac{L_2}{AGC_1}\right\}^{\frac{1}{2}}\left\{1 + \frac{R_1AC_1}{L_1}\right\}^{-\frac{1}{2}} \quad (19)$$

Untuned circuits.—It has already been pointed out that the quantities x and y in equation (24) are both negative with normal coupling, which means that the frequency of the oscillations must be below the resonant frequencies of both grid and anode circuits. This interesting fact may be verified experimentally, and it follows that the resonant frequency of the untuned circuit must be higher than the highest frequency it is desired to produce.

Conversely, with reversed coupling the quantities x and y are both positive, and the frequency of the oscillations is above the resonant frequencies of both grid and anode circuits. The resonant frequency of the untuned circuit must therefore be lower than the lowest frequency it is desired to produce.

The value of z for an orthodyne generator with tuned grid and untuned anode is

$$z = \tfrac{1}{2}\left\{\frac{R_4L_1}{AL_2} + \frac{L_1}{AGC_2}\right\} \quad . \; . \; . \quad (20)$$

and similar formulæ can be found for other arrangements involving one tuned and one untuned circuit.

If probable values are allotted to the various quantities appearing in equations (19) and (20) it becomes apparent that the frequency variations should be less with one tuned circuit than with two. This is confirmed in practice, although the actual difference is less than might be expected from the equations.

It must be observed, however, that there is no means of knowing that the two tuned circuits are actually adjusted in the manner assumed in the above investigation, and it may easily happen in practice that one of the circuits is slightly mistuned, which would easily account for the experimental results. The problem is further complicated by the fact that R_2, the damping of the grid circuit, is certainly not a constant but varies with the amplitude. A full investigation of the effect of these factors would, however, be beyond the scope of the present paper.

Changes in Grid Potential.

It has already been pointed out that the damping in the grid circuit may be divided into two portions—a fixed portion which includes the true ohmic resistance of the coil and the dielectric losses in coil and condenser, and a variable portion depending on the grid current in the valve itself.

Under normal working conditions the damping due to the grid current is usually larger than the damping due to other causes, and in any case the latter can be kept down to a very low figure by suitable methods of construction. The question of keeping down the damping in the grid circuit is therefore mainly a question of keeping down the grid current in the valve, that is to say, of maintaining the grid at a suitable negative potential.

In the case of a generator with two tuned circuits the quantity z which has been introduced to measure the frequency variation contains the factor $\sqrt{R_2}$, and in the case of a generator with one untuned circuit z contains the factor R_2 without the square root.

In either case the damping in the grid circuit is of fundamental importance, since it determines the whole scale on which the frequency variations occur.

Part III.

IRREVERSIBLE VARIATIONS OF FREQUENCY.

In Part II it was assumed that the E.M.F. generated in the valve is a true sine curve, and it was shown that a frequency variation occurs, the direction of which is dependent upon the nature of the coupling. It is now proposed to consider certain variations which arise in consequence of the fact that the E.M.F. actually generated is not sine-shaped. These frequency variations are irreversible, that is to say, the direction of the frequency change is independent of the direction of the coupling.

The departures from the true sine curve are of two kinds :—

(i) The E.M.F. generated by the valve does not resemble a complete sine curve, but approaches more or less closely to a succession of positive half-cycles with the negative half cycles omitted. Frequency variations connected with the unidirectional character of the impulses appear to be next in order of importance to the reversible variations already dealt with. They are of two types, which will be described as frequency variations of the *second and third types* respectively.

(ii) The E.M.F. generated in the valve may not be sine-shaped at all, but may be distorted. Frequency variations which appear to be associated with this condition will be referred to as belonging to the *fourth type*.

Frequency Variations of the Second Type.

In the case of a generator employing a tuned grid and untuned anode the resonant frequency during the periods when the valve is active is given by the equation

$$f_1 = \frac{1}{2\pi\sqrt{(L_2\sigma C_2)}} \quad . \quad . \quad . \quad . \quad (21)$$

whilst the resonant frequency when the valve is inert is

$$f_2 = \frac{1}{2\pi\sqrt{(L_2 C_2)}} \quad . \quad . \quad . \quad . \quad (22)$$

this second frequency being necessarily lower than the first.

The mean resonant frequency, on which the actual frequency of the oscillations is based, lies between

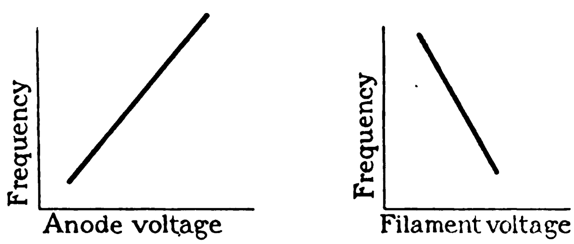

Fig. 8.—Variation of the second type.

these two values, the true figure depending upon the proportion between the period of activity and the period of inertness. This in turn varies according to the conditions under which the circuit is operated, the rule being that the frequency is increased by conditions which increase the period of activity of the valve, and diminished by conditions producing an opposite effect.

An increased anode voltage moves the characteristic curve of the valve towards the left of the diagram, increases the period of activity, and thereby increases the frequency, whilst increased filament voltage alters the conditions in an opposite direction and reduces the frequency (see Fig. 8).

It is assumed throughout this investigation that the energy absorbed by the grid circuit is negligible compared with that absorbed in the anode circuit, and on this assumption the activity (or otherwise) of the valve has no effect on the inductance of a tuned anode circuit. Frequency variations of the second type will not occur therefore when the grid circuit is untuned.

A generator employing two tuned circuits appears to occupy an intermediate position, and a frequency

variation of the second type may be expected to give evidence of its existence.

Frequency Variations of the Third Type.

When a thermionic generator employs a tuned anode circuit the resonant frequency of the anode circuit when the valve is active is

$$f_1 = \frac{1}{2\pi}\sqrt{\left[\frac{1}{L_1C_1} - \frac{R_1^2}{L_1^2}\right]} \quad . \quad . \quad . \quad (23)$$

whilst the resonant frequency when the valve is inert is

$$f_2 = \frac{1}{2\pi}\sqrt{\frac{1}{L_1C_1}} \quad . \quad . \quad . \quad . \quad (24)$$

the second frequency being always higher than the first.

The mean resonant frequency, on which the actual frequency is based, lies as before between these two values.

It will be observed that the frequency variations of the second and third types are always in opposite directions (see Figs. 8 and 9).

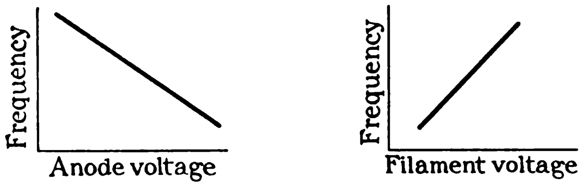

Fig. 9.—Variation of the third type.

Frequency variations of the third type do not occur when the anode circuit is untuned, but they occur whenever the anode circuit is tuned, independently of whether the grid circuit is tuned or not.

Frequency variations of the fourth type.—The effect of harmonics on the resonant frequency of a thermionic oscillator has been examined by Appleton and Greaves,* one of the arrangements discussed being equivalent to a tuned anode circuit. Analogous problems have also been discussed by other investigators. The result is to show in each case that the resonant frequency is reduced by the presence of harmonics.

Bearing in mind that the period of activity is an indefinite fraction of a complete cycle, it is difficult to say what conditions of operation are likely to produce the largest proportion of harmonics.

On the experimental side the effect seems to be of less importance than the variations of the second and third types, and no case has come to the author's notice in which the presence of harmonics can be said to have produced a definite variation of frequency.

Part IV.

THE DESIGN OF RHEODYNE THERMIONIC GENERATORS TO COVER A WIDE BAND OF FREQUENCIES.

Introduction.

A circuit diagram of a thermionic generator with resistance coupling between the oscillatory circuits has already been given in Fig. 5, and other arrangements are shown in Figs. 10, 11 and 12.

* E. V. Appleton and W. M. H. Greaves: *Philosophical Magazine*, 1923, vol. 45, p. 401.

It is essential that the capacities of the two oscillatory circuits should be connected to one end of the resistance and the two inductances to the other, but it is immaterial which.

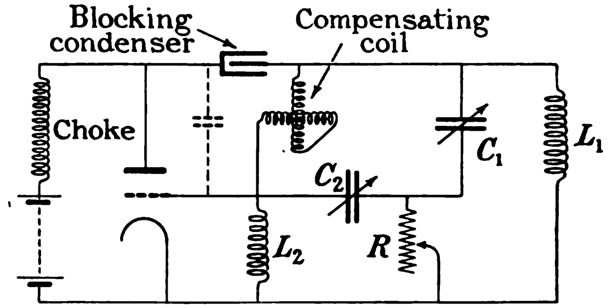

Fig. 10.

In order that the resistance coupling may generate oscillations in the manner indicated in the circuit diagrams, it is, of course, necessary that the coupling

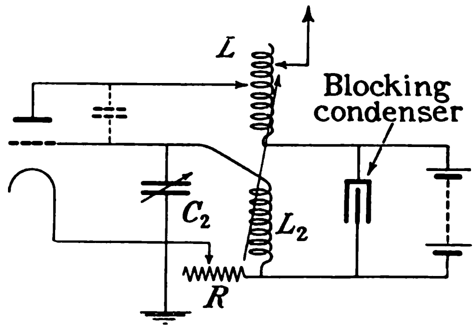

Fig. 11.

due to stray capacity should be neutralized. This may be done in various ways :—

(i) By reversed inductive coupling, as shown in Figs. 5 and 11.
(ii) By providing an inductive path between grid and anode, as shown in Fig. 10.
(iii) By what are generally known as neutrodyne circuits, such as the circuit shown in Fig. 12.

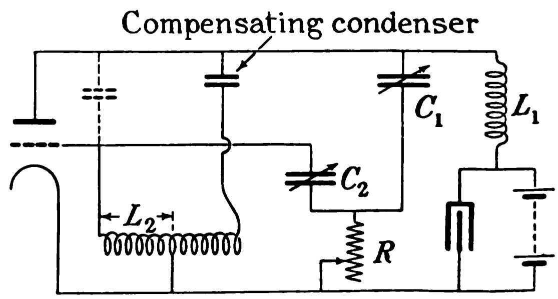

Fig. 12.

The problem of neutralizing stray capacity coupling is well known in connection with the design of amplifiers, and it is not necessary to discuss it here in detail. It may be observed, however, that the measurement of

the frequency variations when a circuit is oscillating provides a convenient method of determining whether the capacity coupling has been accurately neutralized or not. It also gives definite information as to whether the neutralizing arrangement is insufficient or excessive.

It is interesting to note in passing that the energy absorbed by the coupling resistance is approximately equal to the energy absorbed by the grid of the valve, so that the additional energy required to operate the circuit is not of material importance. Apart from the energy absorbed by the coupling resistance, the circuit operates under conditions of maximum efficiency.

The circuit generates oscillations of full amplitude and is applicable to transmitters, master oscillators, and wave-meters, and it may also have applications to amplifiers.

In order that a rheodyne generator may work efficiently it is necessary that :—

(i) The potential on the grid should be independent of the frequency, or nearly so.
(ii) The stray capacity should be correctly neutralized, or nearly so.

In order to ascertain whether this could be done without varying the coupling resistance or the neutrodyne arrangement, a special investigation was made on these two points. It is not proposed to give the details of this investigation, but the results will be briefly summarized.

Generator without Anode Tap: Adjustment of Grid Potential.

If the coupling resistance R is to remain constant it can be shown that the same method of tuning must be adopted for both grid and anode circuits, but the use of condenser tuning for the grid and variometer tuning for the anode, or vice versa, is inadmissible.

Provided this condition is satisfied there will always be a particular frequency for which the coupling resistance will be a minimum, and if this minimum is not in the centre of the desired band it can be made so by altering the value of the grid coil or condenser, as the case may be. It is only necessary to observe the value of L_2/C_2 at which the minimum actually occurs, and to alter the circuit so that it has this value at the particular frequency desired.

Generator with Anode Tap: Adjustment of Grid Potential.

When the anode circuit is tuned by means of a tapped coil, and the connection to the anode of the valve is made by means of an adjustable anode tap, it is immaterial whether the tuning of the grid circuit is by variable condenser or variometer. In either case the grid circuit can be so adjusted that R has a minimum value at any desired frequency.

A practical point may be noted in passing. If the grid is to be tuned by means of a variable condenser it may be found that the correct value of the condenser is inconveniently large. The difficulty can, however, be overcome by adopting a convenient size of condenser and by connecting the grid to an intermediate tapping point on the coil.

Generator Tuned by Variable Condensers: Neutralization of Stray Capacity.

The problem of neutralizing the coupling due to stray capacity is well known in connection with the design of amplifiers, and the circuit commonly used is shown in Fig. 12.

The capacity of the compensating condenser is of the same order as the stray capacity, that is to say, it is small compared with the other capacities in the circuit.

It follows that the current through the compensating condenser is mainly determined by the capacity of the compensating condenser itself, and it may be assumed as a first approximation that the fall of potential across the compensating coil is small compared with the fall of potential across the compensating condenser.

Assuming further that there is close coupling between the two coils, then

$$\frac{C_4}{C_5}=\frac{L_5}{M_2} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

where C_4 is the stray capacity, C_5 the capacity of the compensating condenser, L_5 the inductance of the compensating coil, and M_2 the mutual inductance of the compensating coil and the grid tuning coil. Within certain limits the compensation is sensibly unaffected by the tuning.

It will be found in practice, however, that the compensation is not strictly constant on all frequencies. The inductance of the compensating coil increases the current through the compensating condenser by an amount which varies with the frequency, and which is greater for high frequencies. For a given adjustment, therefore, the compensation is excessive at high frequencies.

To minimize this effect it is desirable to keep the resonant frequency of the compensating circuit as high as possible, and it is clear from equation (25) that this depends on reducing M_2. It is therefore desirable to work with small coils and large condensers.

The method described is applicable to any type of generator employing a fixed grid coil in conjunction with a variable condenser, and it is immaterial whether anode tuning is by means of a variable condenser or by a tapped coil.

Generator Tuned by Variable Inductances: Neutralization of Stray Capacity.

When a generator is tuned by means of inductances or tapped coils it can be shown that the condition for the correct neutralization of the stray capacity is that M/L_1 must be kept constant, where M is the mutual inductance and L_1 the inductance of the anode coil.

The arrangement of the design so that this condition is fulfilled does not appear to present any serious difficulty.

Part V.

DESIGN OF ANTIDYNE THERMIONIC GENERATORS TO COVER A WIDE BAND OF FREQUENCIES.

Generator with Tuned Grid and Tuned Anode.

The orthodyne thermionic generator necessarily employs a combination of capacity and inductive coupling. Capacity coupling increases with the frequency not only over the band of frequencies covered by any individual instrument, but also as between similar instruments designed for different bands of frequencies. The strength of inductive coupling depends upon the method of tuning adopted. When tuning is carried out by means of variable condensers the inductive coupling is stronger at the lower frequencies than at the higher.

On frequencies of the order of 1 000 kilocycles per second fairly uniform coupling is obtainable over a wide band of frequencies by a suitable adjustment of the two couplings, the capacity coupling providing the greater part of the required coupling at the higher frequencies, and the inductive coupling performing the same function at the lower frequencies. This principle may also be applied to the design of antidyne circuits.

It has already been explained that there is a well-known form of neutrodyne circuit in which a small condenser controls the magnitude of the current flowing from anode to grid and in which a transformer reverses its direction. If a circuit of this type is so adjusted as to produce a coupling greater than the stray capacity coupling, the resultant is a form of coupling which is opposite in direction to normal capacity coupling, but which possesses the same general properties. The arrangement may therefore be described as reversed capacity coupling.

An antidyne thermionic generator which is required to cover a wide band of frequencies should make use of a combination of reversed capacity coupling and reversed inductive coupling, and its design will then be governed by the same principles as those which apply to generators using normal coupling. In practice the reversed capacity coupling is therefore so adjusted as to ensure sufficient reaction at the higher frequencies, and the reversed inductive coupling is so adjusted as to give sufficient reaction at the lower frequencies. Finally the grid leak is adjusted to such a value that the required balance is obtained between the reversible and irreversible effects as already explained.

Generator with Untuned Anode or Untuned Grid.

It has already been shown that with reversed coupling the resonant frequency of the untuned circuit must be below the lowest frequency it is desired to produce, and this condition is the controlling factor in the design of such circuits. At this point it may be desirable to emphasize the difference between tuned and untuned circuits. With tuned circuits the currents in the capacity and the inductance respectively are opposite in direction and nearly equal in magnitude, so that the oscillatory current may be many times larger than the current flowing through the valve. The impedance of the tuned circuit is therefore much higher than the impedance of either inductance or capacity alone. With untuned circuits this is not so, and the flow of current in capacity or inductance is only balanced to a very limited extent.

The capacity of an untuned circuit must therefore be small, especially at high frequencies, or the fall of potential across the circuit will be so low that the alternating potential on the grid will be insufficient to maintain the oscillations. To bring the untuned circuit with its small capacity to resonance would require an anode coil considerably larger than the tuned coil, while to produce an untuned circuit whose resonant frequency is below the lowest frequency for which the instrument is designed requires a still larger coil. An untuned coil of specially high inductance is therefore an essential feature of circuits of this type. The importance of this point may be emphasized by an actual example. With an instrument covering a band of frequencies from 600 to 1 500 kilocycles the tuned circuit might consist of a coil having an inductance of 140 μH in combination

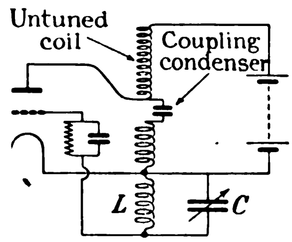

Fig. 13.

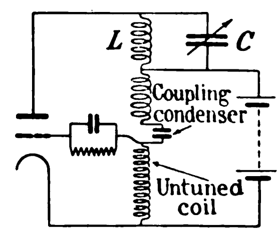

Fig. 14.

with a variable condenser having a maximum capacity of 500 $\mu\mu$F.

With normal coupling the untuned coil might have an inductance of 140 μH or less, depending on the closeness of the coupling.

With reversed coupling, and a capacity of 50 $\mu\mu$F in the untuned circuit, the minimum value of the inductance would be 1 400 μH, and this would just give resonance at the lowest frequency. In practice a coil of about 5 000 μH would probably be used so as to avoid certain effects which appear if resonance is approached too closely.

The value of the untuned coil having been fixed, the best value for the reversed capacity coupling and the reversed inductive coupling can be determined by trial, remembering that the reversed capacity coupling is most effective at the higher frequencies and the reversed inductive coupling at lower frequencies of the band which it is desired to cover.

A circuit diagram of an antidyne generator with untuned anode is given in Fig. 13, and with untuned grid in Fig. 14.

Part VI.

EXPERIMENTAL RESULTS AND PRACTICAL APPLICATIONS.

Rheodyne Generators.

The experimental thermionic generator employed an R valve: filament voltage 3·8 to 4·2, anode voltage 40 to 200, no grid bias unless stated. The frequency of the oscillations was about 5×10^6.

The results are shown in Figs. 15 to 20, and a comparison of these results with the theoretical diagrams, given in Figs. 7, 8 and 9, suggests that the actual frequency variations are due to a combination of the variations of the first and second types.

The frequency variations which are produced by changes of filament voltage are of a simpler character than those produced by changes in anode voltage, as on the frequency, and only so much reversed coupling is employed as is necessary in order to obtain a balance between the variations of the first and second types. The correct adjustment for constant frequency gives Fig. 18.

The practical application of these results will be discussed more fully in a later Section.

Fig. 17 is of special interest as it shows a variation

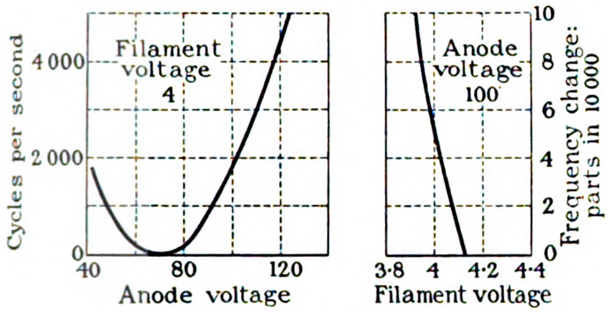

FIG. 15.—Normal coupling.

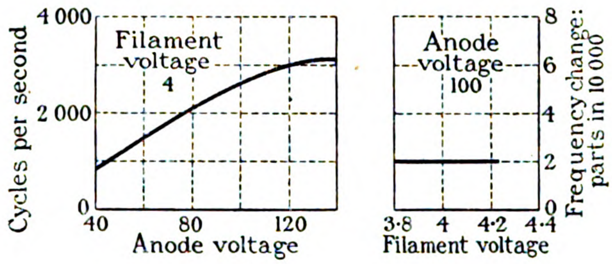

FIG. 18.—Three-quarters resistance coupling, one-quarter reversed coupling.

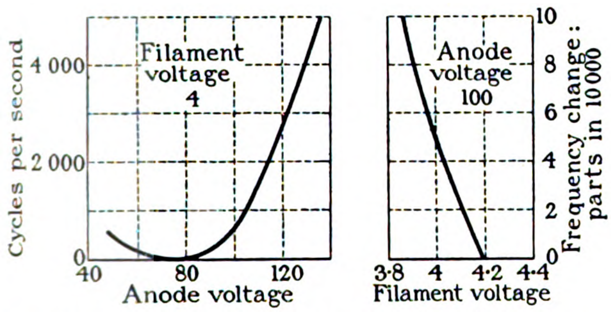

FIG. 16.—Half normal coupling, half resistance coupling.

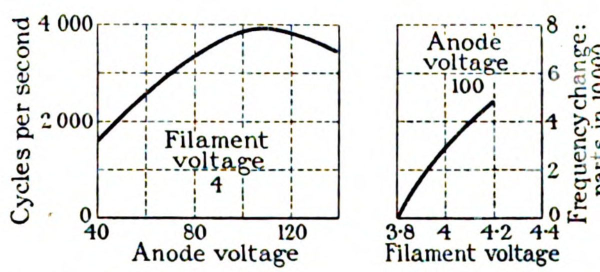

FIG. 19.—Half resistance coupling, half reversed coupling.

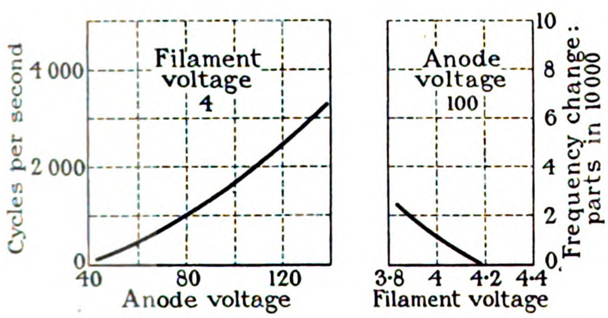

FIG. 17.—Resistance coupling.

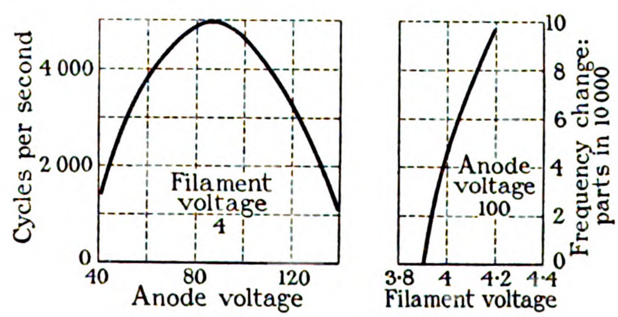

FIG. 20.—Reversed coupling.

[NOTE: In Figs. 15–20 the frequency was approximately 5 000 kilocycles per sec.]

the relationship involved is very nearly linear. With normal coupling the variations of the first and second types are of the same sign, and the total frequency variation is the sum of the two separate effects.

With reversed coupling the variations of the first and second types are of opposite sign, and they can be made to neutralize each other if they are of the same magnitude.

In the method now under consideration advantage is taken of the fact that resistance coupling has no effect of the second type, the variation of the first type being entirely absent.

ORTHODYNE GENERATOR USING GRID BIAS.

The influence of grid damping as a factor in producing irreversible frequency variations has been explained in Part II. Generators which work under such conditions that the grid current is very small may therefore be expected to show important reductions in the frequency variations.

The experimental discovery of this fact appears to be due to the Marconi Company, but details of their experiments have not been published. The author understands that a good deal of work has also been carried out in connection with this subject in America.

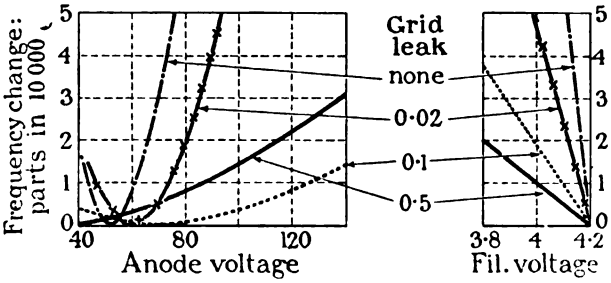

FIG. 21.

The results of the author's own experiments with an orthodyne generator using two tuned circuits are shown in Fig. 21. Similar results for an orthodyne circuit with untuned grid are shown in Fig. 22, and with untuned anode in Fig. 23.

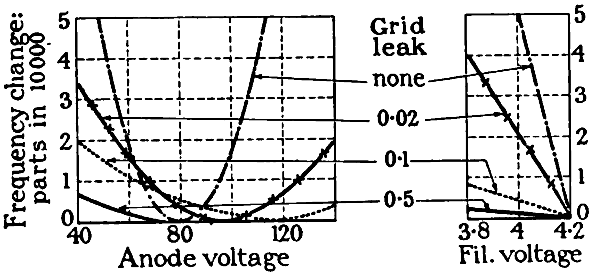

FIG. 22.—Orthodyne generator; untuned grid, tuned anode.

The general character of the experimental results is in good agreement with the theory already given, and the effect of grid bias in eliminating variations of the first type is well shown. It will be noticed that the frequency variations are larger with two tuned circuits than when one circuit is untuned.

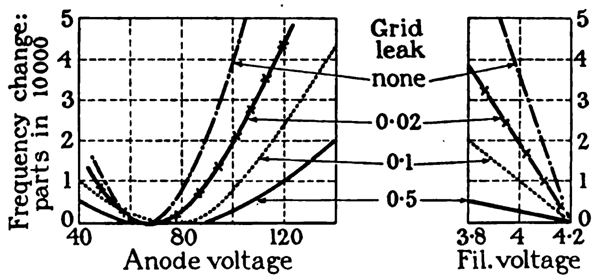

FIG. 23.—Orthodyne generator; tuned grid, untuned anode.

In the case of the generator with two tuned circuits (Fig. 21) and also in the case of the generator with untuned anode (Fig. 23) the results can be regarded as being due to a combination of the variations of the first and second types. For changes of filament voltage the two variations are of the same sign, and an absolutely constant frequency characteristic seems to be unattainable.

In the case of the generator with untuned grid (Fig. 22) the results can be regarded as being due to a combination of variations of the first and third types. For changes of filament voltage the two variations (see Figs. 6 and 9) are of opposite sign, and they can be made to neutralize each other. For changes of anode voltage exact neutralization requires the use of a high anode voltage, that is to say a voltage nearly high enough to stop the oscillations altogether.

This circuit is of great practical importance and seems likely to come into general use for wave-meters and master oscillators. The use of heavy grid bias, however, reduces the amplitude and renders it less suitable for actual transmitters.

ANTIDYNE GENERATOR USING GRID BIAS.

Figs. 24 to 26 show groups of curves for an antidyne generator, and, after what has already been said, it is

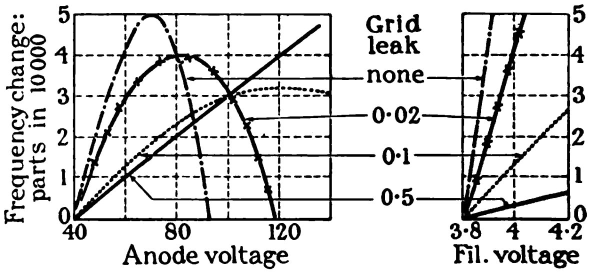

FIG. 24.—Antidyne generator; grid and anode both tuned.

hardly necessary to analyse these curves in detail. Certain points of interest may, however, be noted.

Taking the question of the generator using two tuned circuits, a comparison between Figs. 21 and 24 shows that the frequency variation of the second type is definitely in evidence, so that the total variation for any particular grid bias is less in the latter case than

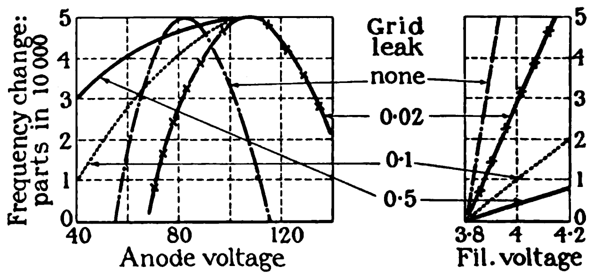

FIG. 25.—Antidyne generator; untuned grid, tuned anode.

in the former. The experiments lead to the conclusion that there is a definite advantage in using reversed coupling rather than normal coupling.

This conclusion would no doubt apply to arrangements in which the grid and anode are directly connected to different points on the same oscillatory circuit; that is to say, the frequency variations with the Colpitts circuit would be less than with the Hartley circuit.

Passing to circuits which use untuned grid or untuned anode, the antidyne generator with untuned anode which balances the variation of the first type against

the variation of the second type should be compared with the orthodyne generator using untuned grid which balances the variation of the first type against the

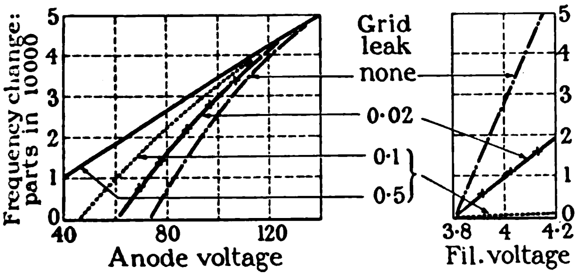

FIG. 26.—Antidyne generator; tuned grid, untuned anode.

variation of the third type. Probably the disadvantage of using an untuned anode would generally outweigh the advantage of using less grid bias.

PRACTICAL APPLICATIONS.

The practical applications of these results fall into two main classes, namely wave-meters and transmitters, the latter term including master oscillators.

In the case of power-driven generators the high-tension and low-tension current will usually be obtained from the same machine, and changes of high-tension and low-tension voltage will presumably be of the same character. It is possible, therefore, to balance changes in anode voltage against changes in filament voltage, and a very close regulation should be obtainable in this way.

Assuming a 10 per cent variation in the voltage of supply it seems quite possible to reduce the frequency variations to something of the order of 1 in 50 000, or 200 cycles per second at a frequency of 10 000 000.

In the case of the heterodyne wave-meter a lower order of accuracy is likely to prove sufficient. The instrument would be so adjusted as to make it independent of variations in filament voltage, leaving only the residual frequency variations associated with changes of anode voltage. These are considerably reduced by the adjustments made in connection with the filament voltage, and are of the order of 1 in 20 000 for a change of 10 per cent in the voltage of supply. If necessary they may be still further reduced by using a high anode voltage, that is to say one which is nearly high enough to stop the oscillations altogether.

Three solutions of the problem of constructing a constant-frequency generator have been referred to :—

(i) The rheodyne generator.
(ii) The orthodyne generator with grid bias, and untuned grid circuit.
(iii) The antidyne generator with grid bias.

These three methods have not yet received sufficient trial to enable one to speak very decisively as to their merits, but their probable advantages and disadvantages may be indicated.

Rheodyne generator.—This is more complicated than most types of orthodyne generator, as it involves the use of two tuned circuits and an arrangement for neutralizing the stray capacity coupling. It does not, however, impose any restriction on the amplitude of the oscillations, and appears to be specially applicable to small transmitters in which it is not desired to incorporate a master oscillator.

Orthodyne generator.—The heavy grid bias required to develop the constant-frequency characteristic in an orthodyne generator with untuned grid involves a considerable reduction in the amplitude of the oscillations, and this renders the arrangement unsuitable for use in actual transmitters. Its simplicity and the fact that it only employs one tuned circuit are important advantages, and it seems probable that it will be extensively adopted for wave-meters and master oscillators.

The position of the *antidyne generator* with grid bias is rather difficult to define. The Colpitts circuit with suitable grid bias seems to have considerable possibilities, but the author is unable to say whether a sufficiently constant frequency is obtainable without some sacrifice of amplitude. The antidyne generator with untuned anode appears to be less advantageous than the orthodyne generator with untuned grid.

FUTURE POSSIBILITIES.

The employment of a thermionic generator which will keep its wave-length constant within 1 part in 50 000 makes heterodyne reception possible on wave-lengths of 30 m or less, and the production of such a generator now appears to be a practical possibility.

Variations in wave-length due to changes in aerial capacity have already been reduced to a low figure by the use of master oscillators, and the employment of a constant-frequency circuit for the master oscillator would appear to remove any troubles connected with the voltage of supply.

The development of heterodyne wave-meters which will give an accuracy of 1 part in 10 000 is another interesting possibility. There are a number of details in the design of such an instrument which require further study, and which cannot be discussed here. Now that variations connected with the voltage of supply have been removed, however, there is no reason to suppose that any of the outstanding difficulties are insuperable.

For proper modulation, radio-telephony requires a band of 10 000 or 20 000 cycles, but a very much narrower band is theoretically sufficient for wireless telegraphy, and the number of channels of communication which is theoretically available on the shorter wave-lengths is very great.

The number of channels actually available at the present time does not approach these theoretical limits, but is determined by the unavoidable variations in the wave-length of our transmitters. Any method which will reduce the variations in wave-length of short-wave transmitters will automatically increase the number of channels of communication available for practical use.

The author would like to take this opportunity of thanking various friends who have assisted him from time to time with criticism and advice, and especially Major A. G. Lee of the Post Office Engineering Department, who has made a number of helpful suggestions.

APPENDIX.

Anode circuit.—Referring to Figs. 2 and 3, and ignoring the circuit $L_3R_3C_3$ in Fig. 3, put

E = E.M.F. in the valve,
E_1 = E.M.F. across C_1,
E_2 = E.M.F. across L_1,
I = current through the valve,
I_1 = current through C_1,
I_2 = current through L_1.

Then
$$I = (E - E_1)/A$$
$$I_1 = jE_1C_1\omega$$
$$I_2 = E_1/(R + jL\omega) = E_2/jL\omega$$
$$I = I_1 + I_2$$

If ϕ is the phase angle between E_2 and E, then it can be shown that

$$\tan\phi = \frac{-A(LC\omega^2 - 1) + R}{L\omega + ARC\omega} \quad . \quad . \quad . \quad (26)$$

Now put $\omega = \omega_0(1 + y)$ and we get

$$\tan\phi = \frac{-2Ay + R}{\sqrt{(L/C)} + AR\sqrt{(C/L)}}$$

which is the form of equation (2) on page 350.

Anode oscillatory circuit.—A combination of the results shown in equations (29) and (2) leads to the result

$$\tan\phi = -\frac{2Ay\sqrt{(L/C)}}{(L/C) + AR}$$

which is the form of equation (3) on page 350.

Acceptor circuit.—The circuit is supposed to consist of a coil of inductance L and resistance R in series with a capacity C.

The complex resistance of the whole circuit is $\{R + j(L\omega - 1/C\omega)\}$, and the phase angle between current and E.M.F. is

$$\text{arc tan}\,\frac{LC\omega^2 - 1}{RC\omega}$$

The potential across C lags 90° behind the current, and the phase angle between this potential and the applied E.M.F. is given by the equation

$$\tan\theta = \frac{RC\omega}{LC\omega^2 - 1}$$

where θ is an angle between 180° and 360°.

If ω is near the resonant frequency ω_0, put $\omega = \omega_0(1 + x)$, where x is a small quantity, then

$$\tan\theta = \frac{R\sqrt{C}}{2x\sqrt{L}}$$

which is the form of equation (4) on page 351.

Discussion before the Wireless Section, 6 January, 1926.

Major A. G. Lee: For some time past it has been recognized that an ordinary valve transmitter is liable to large frequency-changes which are caused by unavoidable variations in filament current and anode voltage. In order to overcome this difficulty I have devised another solution * which consists in obtaining harmonics from a valve-maintained tuning-fork oscillator, selecting a particular harmonic and amplifying it for transmission from the antenna as the wireless frequency. This system is now in use at the Northolt, Devizes and Rugby valve stations. The author has attacked the problem more directly and fundamentally. It may be of interest to get a physical idea of the processes involved in these frequency-changes which have been worked out mathematically and experimentally in the paper. The simplest case to analyse in this fashion is that of the tuned grid, untuned anode, oscillator. If we start with a voltage E_g of a certain phase on the grid, there will be an E.M.F. in the anode circuit of $-\mu E_g$, the minus sign denoting 180° phase change. Now, if the anode circuit were resistive only, the current in that circuit would be in phase with the E.M.F., and this would in turn produce an induced E.M.F. in the grid tuned circuit of phase + 90°. The current in the tuned circuit due to this E.M.F. would be in phase with it, and therefore the voltage across the condenser, which is also that across the grid and filament, would be in phase with the E.M.F. we started with, E_g. Now if we have regard to the actual conditions in the anode circuit we see that, due to the inevitable inductance coil in it, the current is out of phase with the E.M.F. generated in the anode circuit by the valve. This out-of-phase current may be regarded as introducing a reactive component into the tuned circuit, and if we desire to retain the original frequency of E_g from which we started, we can correct the phase by mistuning the circuit. Actually what is happening is that the system oscillates at some frequency other than that to which the circuit is tuned. Now we can see that if any changes of filament current or anode voltage occur, of sufficient magnitude to alter the anode resistance, the phase of the current in the anode circuit will be altered and the circuit will oscillate on a different frequency. This phase effect is the major one of the several causes, referred to in the paper, which operate to change the frequency of oscillation. The remedy for the "phase" effect is to ensure that the grid and plate alternating voltages are always 180° apart in phase, and the conditions for this adjustment have been worked out in the paper. If, for example, in the above-mentioned case of an untuned anode, the anode circuit were resistive only, any alteration of anode resistance would not change the phase, and no alteration of frequency would result. Figs. 2, 4 and 5 are of interest because they are all circuits with two degrees of freedom, and we should expect, at first sight, to have two modes of oscillation. In the case of Figs. 2 and 4, however, the phase relation-

* A. G. Lee: "Tuning-fork Generator at Northolt," *Electrician*, 1925, vol. 94, p. 510.

ships are such that the circuits will not oscillate on one of the modes of oscillation. In Fig. 5, when the two circuits are identical, there is again only one mode of oscillation possible, that in which the current circulates round the inductances and capacities in the circuit. The current does not pass through the resistance, because the two ends of the resistance are at the same potential (with actual physical circuits possessing resistance there will be a small difference of potential across the ends of the shunting resistance and a small current will pass through it). The other type of possible oscillation, in which the main current passes through the shunting resistance, puts the grid and anode at the same potential, a condition in which the valve will not maintain oscillations. This is also a very interesting circuit to analyse physically. It may be regarded as a development of the Colpitts oscillator, Fig. A. In this circuit the

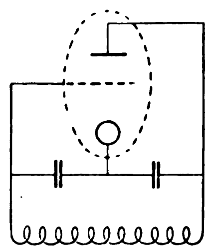

FIG. A.

grid-filament and anode-filament resistances may be represented as resistances shunted across the two condensers, as shown in Fig. B. It is fairly easily seen that these shunting resistances will affect the frequency of oscillation, and if they vary in magnitude with the voltage of supply the frequency generated will also vary. The author's solution is to join the points A, B, by a small resistance so as to bring these points to nearly the same potential, and the theoretical circuit corresponding to this case is shown in Fig. C. It will be seen

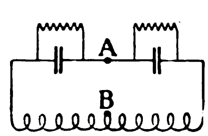

FIG. B.

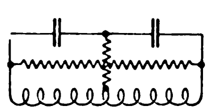

FIG. C.

that the valve resistances are now symmetrical with regard to both the capacities and inductances and the circuit will oscillate at its natural frequency, which will not be changed by any alterations in voltage. With regard to the frequency variations of the second and third types, I have been unable to deduce equations (21) and (23). So far as I understand the argument in regard to these variations, they are due to the fact that the actual frequency generated is a mean between that obtained during the portion of the cycle when the valve is passing current and the other portion when it is not passing current. Also any changes which affect the length of the fraction of a cycle during which current is passed will affect the value of the mean frequency. It would therefore appear that equations (21) and (23) should contain an expression for the valve conductances as affecting the phase and, therefore, frequency generated. A circuit which would appear to give most of the conditions for constant frequency is the "Dynatron" circuit. This circuit would appear to be free from the major variation due to phase shift. I think that the able analysis of the effects causing frequency shift made by the author will be of considerable assistance in the design of short-wave oscillators and heterodyne wave-meters.

Mr. G. Shearing: The experimental results for a low-power valve generator given in Part VI of the paper comparing the frequency-changes of the various types of circuits with capacity, inductive, and resistance coupling, are very interesting and they appear to favour on the whole the adoption of the resistance type of coupling with subsidiary compensating coupling for stray capacity for a constant-frequency generator. On the other hand, the remarks under the heading of "Practical Applications" leave one rather in the dark as to which type of circuit the author would really adopt for a constant-frequency generator. For the resistance type of coupling, e.g. that shown in Fig. 10, and stated to be applicable to transmitters, master oscillators and wave-meters, I do not think it is clear that the circuit would be a very

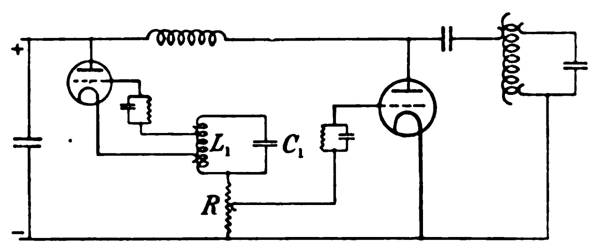

FIG. D.

efficient power generator of any magnitude, for, if the circuit C_2L_2 only carries a small proportion of the main oscillatory current, I should expect the power loss in the resistance R to become considerable for even a medium-power transmitter. On the other hand, if the circuit C_2L_2 carries a current of value equal to or greater than that in R, then the size and cost of the circuit C_2L_2 may become considerable for a small power loss. Also, how would the author couple such a circuit to the next stage of a power-amplifier system? Would he couple the grids of the next stage to the resistance R or to the inductance L_1 or capacity C_1? In this connection some of the disadvantages which appear to be attached to the use of the circuit of Fig. 10 for power amplifiers can be overcome by using the unidirectional pulses of valve current rather than the oscillatory current itself for exciting the next stage. The method of effecting this is to generate oscillations in a local oscillatory circuit L_1C_1 placed in series with a resistance R as shown, which carries only the unidirectional pulses of valve current which excite the oscillatory circuit L_1C_1 (see Fig. D). This resistance is not in the local oscillatory circuit, consequently for a suitable high-voltage supply the ohmic loss in this resistance is small. If, now, the grid or grids of the next stage of the power amplifier are connected to this resistance R, the arrangement will function satisfactorily as a power amplifier, the energy required for the grids of this stage being supplied from

this resistance, which in turn receives the energy direct from the high-tension supply. I have found such a power-amplifier arrangement to oscillate with excellent stability and a large step-up ratio; the power loss in the resistance is small by reason of the small proportion of the exciting current to the oscillatory current in L_1C_1. The constancy observed of the wave-length generated has been better than that observed for similar circuits when using inductive or capacity in place of the resistance coupling. As regards the development of a wave-meter circuit, a form of circuit has been described by E. Fromy * in which series inductances and capacities are placed in both grid and anode circuits of the generator valve; these are both coupled inductively to a separate circuit (see Fig. E). All three circuits are tuned to the same frequency and he states, giving experimental results, that, if $L_1C_1 = L_2C_2 = (L + L')C$ with coupling of L_1 and L_2 respectively to L and L' such that the grid and anode voltages are 180° out of phase, then the frequency $f = 1/[2\pi\sqrt{(L + L')C}]$ and is independent of normal changes of anode and filament voltages. The three capacities C_1, C_2 and C may be equal and he suggests for a wave-meter that they be mounted on a common axis for ease of adjustment. The constancy of the frequency is claimed to be due to the introduction of the condensers C_1, C_2, i.e. tuning the grid and anode circuits so that they are equivalent to resistances only.

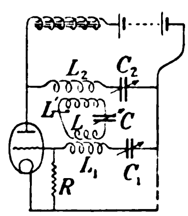

FIG. E.

Variations that may be due to changing the valve itself can be made small by using a capacity in parallel with the grid-anode capacity, and the accuracy is stated to be of the order of 0·001 per cent. The importance of grid and anode oscillatory potentials being at a phase angle of 180° is clearly indicated by the mechanical analogy and other portions of the paper. I do not understand what the author means by the term "E.M.F. generated in the valve," as surely any oscillatory E.M.F. is generated in the reactive portions of the circuits to which the valve is connected and not in the valve itself. The importance of small grid damping has been clearly pointed out in the paper, and as regards power transmitters it is more easy to arrange for small grid damping with power-amplifier circuits with grids operated definitely at a small mean potential than with retroactive circuits. For the circuit of Fig. 5 it is easy to see that the grid-filament and anode-filament oscillatory P.D.'s have the correct phase relation of 180°, but the circuit of Fig. 2 when used as a power transmitter constitutes an inefficient arrangement unless the product L_2C_2 is very much less than the product L_1C_1. The circuit as shown is applied to reception, but in this case the retroactive coupling of grid to anode, usually by means of auxiliary coils, is very small. I do not like the use of the term "complex resistance" in the Appendix, as it appears to me the author might equally well have spoken of "complex reactance." I consider the correct term "impedance" should be used. Also, I think it much better to use the terms resistance, inductance or capacity coupling than to introduce the terms employed by the author for the circuits he has described.

* *L'Onde Électrique*, 1925, 4ᵉ année, p. 433.

Dr. R. L. Smith-Rose: One of the most important problems in the practice of wireless communication to-day is that of the reduction of interference. Two of the contributory causes of interference are (1) that transmitting stations are not on the wave-length (or frequency) allocated to them, and (2) that their transmissions vary in frequency about the mean on which they usually operate. The author refers to this matter but does not give any actual figures, and I should therefore like to draw attention to some of the results obtained at the National Physical Laboratory on measurements obtained some time ago and extending over a period of about 2 months. The measurements were made by Mr. Dye, and a summary of the results was given in the N.P.L. Annual Report for 1924 (p. 79). Some 23 transmitting stations, situated on either side of the Atlantic, were measured, most of them being high-power long-wave stations. The results show a very high degree of uniformity, and in general the variations were less than the actual difference between the mean frequency and the frequency allocated to the station. For example, 10 of the 23 stations showed a mean daily variation of less than 1 part in 1 000, which is quite large compared with the ideal conditions visualized by the author. The actual limits of the mean daily variations were from 0·2 to 3·7 parts in 1 000, whereas the actual difference between the mean frequency and the nominal frequency ranged from 0·1 to as much as 11·4 parts in 1 000 for the 23 stations. Those measurements were only carried on for a period of 2 or 3 months, but they seem to give an idea of the order of the variation which is occurring at the present time. In connection with the rheodyne circuit mentioned in the paper, I do not quite understand what would happen if the two circuits are slightly detuned from one another. Supposing one is detuned a little, to the order of a few parts in 10 000. It would seem that the system would then have two possible oscillation frequencies, and some doubt might exist as to which of these it is operating upon at any given time.

Lieut.-Col. H. P. T. Lefroy: Dr. Smith-Rose has referred to the variation in transmission frequency that occurs on the longer wave-lengths; those that occur on the shorter wave-lengths are still greater, so that any improvements in transmitter design, such as those suggested by the author, which, in a simple manner, will eliminate such variations, will be particularly valuable for small portable sets. For signal discrimination we have at our disposal, in the case of radio-telegraphy, three well-known methods, namely, high-frequency selectivity, low-frequency selectivity and directional selectivity. In practice we can usually only employ high-frequency selectivity, and, in certain cases, directional selectivity, when receiving from portable transmitters. If we try to employ low-frequency

selectivity we find that the note selectors available are quite effective, but that the heterodyne note of the received signals varies so much that the note selector filters out a large proportion of the desired signals, so that we lose the advantage of this available third method of discrimination. Master oscillators have been developed which give satisfactory constancy of transmission frequency, but they increase too much the complication and size and weight of portable sets. Is the author satisfied that his methods can be immediately applied to transmitters up to about 2 kW without serious loss of efficiency, and that such methods can be usefully employed with transmitters that have to work over a wide band of wave-lengths? As regards wave-meters, is it possible, with those made to his design, to continue to use the original calibration scale without perceptible error, after the valve has been changed owing to the filament burning out?

Mr. A. G. Warren: The particular criticism that I have to make is with regard to the author's method of working out the circuit of Fig. 3. He says:—"The problem can be simplified by assuming that the energy absorbed in the grid circuit is negligible compared with the energy absorbed by the anode circuit, so that the flow of current in $L_3R_3C_3$ can be ignored in dealing with the circuit $L_1R_1C_1$." Looking at these circuits it appears that the circuit $L_3R_3C_3$ is a circuit of low impedance, whereas L_1 is of high impedance, and therefore one would expect that the current through the

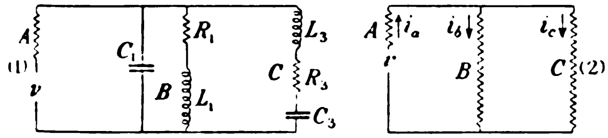

FIG. F.

shunt circuit $L_3R_3C_3$ would be considerable. It is, in fact, considerable unless the coupling between the two circuits is very small. I would suggest another way of dealing with the circuit. Assuming that R_1 is small compared with ωL_1, we may re-draw Fig. 3 as Fig. F [(1) and (2)]. For this circuit we have

$$v = i_a\left(A + \frac{BC}{B + C}\right) \quad \text{and} \quad i_a = i_c\left(1 + \frac{C}{B}\right)$$

whence

$$v = i_c\left\{A + C\left(1 + \frac{A}{B}\right)\right\}$$

Now since C contains the grid condenser (or its equivalent), i_c must be 90° out of phase with V. Therefore the expression $A + C\{1 + (A/B)\}$ must be wholly imaginary, or its real part must be zero. But

$$C = R_3 + j\,.\,2x\sqrt{\frac{L_3}{C_3}}$$

and

$$\frac{1}{B} = \frac{C_1}{L_1}\left\{R_1 + j\,.\,2x\sqrt{\frac{L_1}{C_1}}\right\}$$

Substituting these values, making $L_1C_1 = L_3C_3$, and equating the real part of $A + C\{1 + (A/B)\}$ to zero, we obtain

$$x = \pm\sqrt{\left[\frac{R_2C_2}{4AC_1} + \frac{R_1R_2C_2}{4L_1} + \frac{M^2C_2}{4L_1^2C_1}\right]}$$

Comparing this with the author's equation (7) we see that it includes an extra (third) term. I do not know how this third term compares with the others in practice, but, assuming an R valve with a grid circuit not exceeding a few ohms in resistance, it is greater than the first term unless M is less than 1 per cent of L_1. I imagine that M exceeds this value and that this third term is by no means negligible.

Mr. G. W. N. Cobbold: The author has directed attention to a subject of great and growing importance, upon which little has been published for several years. Attention must be called, however, to the work of Eccles and Vincent published in the *Proceedings of the Royal Society*, A, 1920, vol. 96, p. 455, where a description is given of practical experiments somewhat similar to those described in the present paper. There appear to be certain discrepancies between Eccles's results and those of the author, but I think these are probably due to the fact that Eccles placed the lower limit for his high tension at about 70 volts, whereas the author has limited his low tension to 4·2 volts. This, for the particular coupling he used, did not enable him to reach a stationary value on the frequency/low-tension-voltage curve. These differences are rather important, for the author has concluded that stationary values cannot be obtained when the filament voltage is varied, whereas Eccles has shown that, with suitable couplings and a normal type of circuit, such values can be arrived at. One of the earlier speakers appears to have suggested that the frequency-changes due to voltage variations are apt to be large compared with those due to a change of valve. I find, however, in practice, that with well-designed circuits the variations due to a change of valve are liable to be very much greater than those due to a 10 per cent change of either high-tension or low-tension voltage.

Prof. C. L. Fortescue: With regard to the resistance-coupled circuit, this merely consists of two "acceptors" in series with the resistance connected across the nodes of potential. As is well known, this circuit arrangement has a high resistance at frequencies other than that to which the "acceptors" are tuned. The arguments used in deriving equation (6) are incomplete, in that only the phase relations are considered. In actual fact there must be a magnitude adjustment, with the result that the amplification factor of the valve is necessarily involved and the anode resistance—the A of this paper—must be regarded as a variable.

Mr. C. F. Phillips: The author speaks of an accuracy of 1 part in 50 000, but I should like to know whether such an accuracy is really readable on any wave-meter, what kind of variable condenser is used, and how it is read to the requisite accuracy to give 1 part in 10 000, let alone 50 000, and further, to what extent such condenser maintains its accuracy.

Major B. Binyon: Without detracting from the value of the paper, it should be pointed out that there are other factors quite apart from filament and supply variations which might cause greater frequency variations than 1 part in 50 000. In view of the increasing use of short wave-lengths the whole question of maintaining a constant frequency is a matter of very great importance.

Mr. L. B. Turner (*communicated*): The subject under discussion is the reduction to a minimum of those very small changes in the frequency of a triode oscillator which are apt to be caused by small changes in the supply voltages. In view of the use of the heterodyne at very short wave-lengths the subject has considerable practical importance. Now the possible circuit arrangements of a triode oscillator are many. Mathematical investigation of the exact frequency can be undertaken only for sensibly sinusoidal conditions, and therefore with amplitudes small enough to allow the anode-filament resistance A of the triode to be treated as constant throughout the cycle; and even then, except in the simplest circuit arrangements comprising only a single approximately resonating circuit, the algebra is hopelessly cumbersome. The effect of change of filament or anode voltage is to alter A, generally at the same time making A rather less perfectly constant during the cycle. In order to investigate the effect on the frequency f, we need an expression for f in terms of A and of the circuit dimensions. A number of such expressions are derived in the paper, but the electrical theory behind the formulæ seems to me altogether inaccurate, and the formulæ obtained are certainly sometimes erroneous. I propose to indicate some of the mistakes as I seem to see them. With reference to Fig. 2, the author states (in the advance copies of the paper*): "The circuit $L_1R_1C_1$ being a rejector circuit, its complex resistance is . . ." Such a statement is meaningless unless the place of application of the E.M.F. is specified. As here used, $L_1R_1C_1$ is a rejector circuit as regards the "E.M.F. generated in the valve," but it is at the same time an acceptor circuit as regards the E.M.F. impressed in L_1 from L_2. The author seems here, as elsewhere in the paper, to disregard reaction of the L_2 current on L_1, appearing to think this justified "by assuming that the energy absorbed in the grid circuit is negligible compared with the energy absorbed by the anode circuit." This vitiates any search for small departures of frequency from the simple $4\pi^2f^2 = 1/LC$, which is the purpose of the investigation. A formula, (8), for the frequency is thus derived, for the particular case of $L_1C_1 = L_3C_3 = L_2C_2(1 - M^2/L_1L_2)$. Even if this formula were correct, how could one in practice adjust for $L_1C_1 = L_2C_2(1 - M^2/L_1L_2)$; why is this particular adjustment of special interest; and if it is, why, in the analogous case of Fig. 4, is the different special case of $L_1C_1 = L_2C_2$ taken? I am unable to quote manageable correct expressions for the frequency in the cases of Figs. 2 and 4 [equations (8) and (15)], and I regard these as circuits which should be avoided, i.e. when $L_1C_1 \doteq L_2C_2$. They are too difficult in mathematical analysis and in practice, for the reason that a slight change in f or L or C may turn a large positive reactance into a large negative reactance. I cannot accept the author's gross approximation (page 351, top of col. 2) that the reactance of C_3 is negligible in comparison with the impedance of $L_2R_2C_2$. C. Gutton, in his clear and accurate discussion of triode oscillators in "La Lampe à Trois Electrodes" writes of the arrangement of Fig. 4: "Its characteristic equation is of too high a degree to be easily discussed"—a sentiment which experience has taught me heartily to endorse. With reference to Fig. 5, which is one arrangement for obtaining resistance retroaction, the statement is made that "the frequency is independent of the magnitude of the various resistances," including presumably the anode resistance A, the only one whose effect interests us; but in Fig. 17 large observed alterations of frequency with alterations of filament and anode voltages are shown. I cannot follow the author's reasoning in Part III. This professes to investigate non-sinusoidal conditions, but formulæ (21) and (23) are given—whence they are obtained is not stated—which cannot relate to such conditions, since they do not contain any term expressing the properties of the triode. Probably they refer back to sinusoidal conditions; but if so, again they are erroneous. The correct expressions are:—

For (21), $$f_1 = \frac{1}{2\pi}\sqrt{\frac{1}{C_2[L_2 + (R_2/A)L_1]}}$$

and for (23), $$f_1 = \frac{1}{2\pi}\sqrt{\frac{1 + (R_1/A)}{C_1L_1}}$$

For the former, see Gutton, loc. cit., page 92. For the latter, see Gutton, page 59; or Van Der Bijl, "Thermionic Vacuum Tube," page 274; or Turner, "Outline of Wireless," page 127. The experimental observations are interesting, but they are not used to check the theoretical formulæ. It is not clear from what frequency the plotted "frequency change" is measured. For example, in Fig. 18, where perfect insensibility to filament change was obtained, why is the ordinate steady at 2 instead of at 0? It suggests that the "change" plotted is the difference between the oscillation frequency and the natural or resonant frequency of the oscillatory circuit when the triode is made inactive, as by extinction of filament. If so, perhaps the author would explain how he was able to determine the latter with anything like sufficient accuracy, i.e. to a fraction of 1 part in 10 000, or 0·01 per cent.

Lieut.-Col. K. E. Edgeworth (*in reply*): Several speakers have questioned the validity of various approximations made in deriving the formulæ given in the paper, and it appears desirable that my attitude with regard to this question should be defined. I may therefore explain that the whole treatment in the paper is intended to be qualitative rather than quantitative. The formulæ are intended to show the character of the frequency variations which are liable to occur, and it is not suggested that they are suitable for making exact calculations in particular cases. Apart from other difficulties the value of the quantity A, representing the anode resistance, is not known and cannot be measured, although a rough estimate might possibly be attempted. It may be defined as the reciprocal of the mean conductance of the anode circuit of the valve taken over a complete cycle of oscillation, and such a definition serves to convey some of the difficulties which would be encountered in trying to estimate its magnitude.

There remains the question: To what extent can the results produced by these various approximations be accepted at all? The only reasonable way to answer this question would appear to be by an appeal to experi-

* Since revised for the *Journal*.

ment. If the results indicated by the theory are reproduced in practice, then the theory may be accepted as a working hypothesis until something better is offered. Further, a theory based upon an assumption which is known to be true in a special case may be verified by experiment, and may then be extended, by reason of experimental support, to the more general cases in which the original assumption can only be regarded as a rough approximation. The theories which I have put forward in the paper appear to provide reasonable explanations for the results of my experiments. Time will show whether they can be usefully employed in a wider field.

Major Lee draws attention to the fact that formulæ (21) and (23) do not contain any term involving the valve conductance. The explanation is that the equations refer to the resonant frequency of the tuned circuits employed in deriving equations (6) to (8), and they do not refer to the actual frequency of the oscillations generated. It is agreed, however, that the argument is not very satisfactory, and it might be amended to read as follows :—

Variations of the second type.—In the case of an orthodyne generator with tuned grid and untuned anode the equations given in Part II are modified by writing $\tan \phi = A/(L_1\omega)$ and equation (8) becomes

$$\omega = \frac{1}{\sqrt{(L_2\sigma C_2)}}\left\{1 - \frac{R_2L_1}{2AL_2\sigma}\right\}$$

$$\therefore f_1 = \frac{1}{2\pi\sqrt{(L_2\sigma C_2)}}\left\{1 - \frac{R_2L_1}{2AL_2\sigma}\right\} \quad . \quad . \quad (21a)$$

This equation gives the frequency of the oscillations when the valve is active. The corresponding equation for an antidyne generator with untuned anode is given by writing $\tan \phi = -AC_1\omega$, and then

$$f_1 = \frac{1}{2\pi\sqrt{(L_2\sigma C_2)}}\left\{1 + \frac{R_2C_2}{2AC_1}\right\} \quad . \quad . \quad (21b)$$

In either case, when the valve is inert the frequency is

$$f_2 = \frac{1}{2\pi\sqrt{(L_2C_2)}} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

The factor $1/\sqrt{\sigma}$ in equation (21) is always greater than unity, and its influence on the actual frequency of the oscillations depends upon the proportion between the period of activity and the period of inertness. The argument then proceeds as before.

In the case of the frequency variations of the third type the explanation of the meaning of equation (23) is the same, but some of the approximations used in deriving the equation appear to be erroneous. This question is dealt with more fully below in my reply to Mr. Turner.

Mr. Shearing inquires as to the best type of circuit for constant-frequency generators. I have slightly altered the original wording of the paper to make this point clear. On the question of efficiency the paper contains the rather bald statement that the loss of energy in the resistance is equal to the loss of energy in the grid circuit. The actual analysis on which this statement is based was omitted, as it is rather lengthy and did not appear to be of sufficient importance to be given in detail. It can, however, be made available if required. I have no figures available as to the amount of power absorbed by the grid circuit in actual generators, but I do not think it usually exceeds 10 per cent of the power developed in the anode circuit. The anode circuit of the rheodyne generator could no doubt be coupled to the grid circuit of another valve by any of the well-known methods usually employed for this purpose. Questions of frequency variation due to change in the reactance of the load are beyond the scope of this paper.

The author has not experimented with the Fromy circuit, but is inclined to think that the three separate tuning adjustments would be troublesome in practice.

The assumption that the valve can be regarded as a source of energy has, I think, been used by other writers. The actual source of energy is, of course, the high-tension battery, and the valve is a variable resistance. The method attributes to the valve exactly the same properties as those assumed in the investigations quoted by Mr. Turner.

I cannot agree that the word "impedance" is the correct name for the expression $(R + jL\omega)$, and I would direct attention to an article by Prof. Howe in the January number of *Experimental Wireless*, in which the correct meaning of the word "impedance" is explained. In regard to the new words suggested in the paper, it seems better to coin new words when required, instead of using existing words in several different and inconsistent meanings.

The observations on the wave-lengths of existing transmitting stations given by Dr. Smith-Rose are very interesting and show that there is considerable room for improvement. My experiments indicate that rheodyne circuits can be made to oscillate at two frequencies in much the same way as other circuits, and the result is no doubt due to slight mistuning.

In reply to Col. Lefroy, I am of opinion that the rheodyne generator described in the paper and also the orthodyne generator with untuned grid are both capable of being designed to cover a wide band of frequencies, and I have worked out such details as appear to be likely to influence the design. Most of the important points are referred to in the paper.

When a valve is changed there may be a change of anode resistance and/or a change of capacity. The constant-frequency circuits referred to in the paper are essentially circuits in which the frequency is independent of the anode resistance, and it is evidently immaterial whether the change of anode resistance is due to change of valve or change of supply voltage. Changes of frequency due to changes of valve capacity are of course a different matter, and a discussion of the problem would be beyond the scope of the present paper.

Mr. Warren's difficulty is due to his assumption that the circuit $L_3R_3C_3$ is a circuit of low impedance. When grid and anode circuits are both tuned a very loose coupling is sufficient to generate oscillations, so that the circuit is actually one of high impedance. When grid bias is used the energy absorbed by the grid circuit may be very small indeed, and cases have been brought to my notice in which the grid current is only a few

micro-amperes. It will be seen from the experimental results that changes in grid damping affect the magnitude of the frequency variations but not their general character, and one is therefore able to say that results based on the assumption that the grid current is small are applicable to cases in which the grid current is appreciable. The attempt to improve on my formula by the addition of an extra term might perhaps be referred to Mr. Turner, whose remarks on the complexity of the problem are very much to the point. In any case the extra term would not affect the general argument.

Mr. Cobbold draws attention to the investigations of Eccles and Vincent. The generator employed was an orthodyne generator with untuned grid, and it was found in certain cases that the curve giving the relationship between filament voltage and frequency rises to a maximum and then falls again. It would appear from Fig. 7 of the paper that the phenomenon only occurs when the coupling is very weak. The curves obtained for stronger couplings resemble those given in the paper. In practice there must always exist some factor which limits the amplitude of the oscillations, and the controlling factor is not necessarily the same with strong and weak couplings. There is a very interesting field for investigation in this direction which I have not attempted to explore.

From my remarks at the beginning of this reply, it will be seen that I am in agreement with Prof. Fortescue as to the complexity of the problem and as to the reservations which must be made in regard to the various arguments brought forward in the paper.

In reply to Mr. Phillips the simplest method of increasing the accuracy of the readings is to reduce the band of frequencies covered, by employing a small variable condenser in parallel with a large fixed condenser. If the scale can be divided effectively into 500 parts, it is immaterial whether it is employed to read from 300 to 800 m with an accuracy of the order of 1 in 500, or whether it is used to read from 495 to 505 m with an accuracy of 1 in 25 000.

I quite agree with Major Binyon that there are other problems which require solution in connection with the constant-frequency generator. Perhaps someone will tackle some of them at a future date.

I fully agree with Mr. Turner's views as to the complexity of the general problem, but I am not prepared to agree with his attitude towards approximations. It is not possible to determine the validity of an approximation by an argument in general terms. An approximation involving errors of 5 per cent is better than an approximation involving errors of 10 per cent, and an approximation involving errors of 10 per cent or even 20 per cent is better than nothing at all. In tackling an apparently simple problem like the design of a connecting rod, it may be necessary to make more than one assumption involving errors in excess of 20 per cent. To label an assumption a "mistake" or a "gross approximation" does not settle the limits within which it is capable of being usefully applied. Mr. Turner's attitude towards particular approximations is not consistent. He objects to the assumption that the energy expended in the grid circuit is small, and then puts forward a solution which ignores the grid circuit altogether!

The formula suggested in place of equation (21) of the paper omits the factor $1/\sqrt{\sigma}$ which results from the coupling, and is limited to generators using normal coupling. With these two corrections the formula is equivalent to the one which I have given in my reply to Major Lee. For our present purpose the corrections happen to be vital.

The formula suggested in place of equation (23) is limited to the ideal case in which there is no grid current, but the two formulæ should agree, and I have been led to revise the method of obtaining $\tan\phi$, the expression for which now contains an additional term. I agree that equation (23) is fallacious.

The new equation for $\tan\phi$ gives the solution quoted by Mr. Turner as a special case, and leads to a very interesting solution for the constant-frequency orthodyne generator with untuned grid, which appears to be of sufficient importance to be set forth in detail.

In the case of an orthodyne generator with untuned grid, $\tan\theta = -R_3C_3\omega = -R_2C_2\omega = -R_2C_2/\sqrt{(L_1C_1)}$, which gives

$$y = \frac{1}{2A}\left\{R_1 - \frac{R_2C_2}{C_1}\right\} - \frac{R_1R_2C_2}{2L_1}$$

$$\therefore f = \frac{1}{2\pi\sqrt{(L_1C_1)}}\left\{1 + \frac{1}{2A}\left(R_1 - \frac{R_2C_2}{C_1}\right) - \frac{R_1R_2C_2}{2L_1}\right\}$$

The frequency will be independent of the anode resistance when $R_2C_2 = R_1C_1$ or more fully when $R_4C_2 + L_2\sigma/G = R_1C_1$, which is the constant-frequency generator under sinusoidal conditions. It is difficult to say whether the solution is of much practical importance, but it is suggestive and might be made the basis for further research. It will be observed that there will usually be a difference between the frequency of the oscillations when the valve is active and the frequency when the valve is inert. When the two terms involving the anode resistance cancel out, the difference will be in the sense already discussed in the paper.

In reply to Mr. Turner's last question, the curves given in the paper represent frequency-changes only, and the zero has no significance. It may be added that the various curves which are plotted for convenience on the same diagram are not necessarily referred to the same zero.

ILLUMINATION AND LIGHT.

By A. P. TROTTER, Member.

(SECOND FARADAY LECTURE, *delivered before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 18*th January, before the* NORTH-WESTERN CENTRE 19*th January, before the* IRISH CENTRE (DUBLIN) 21*st January, and before the* WESTERN CENTRE 26*th January,* 1926.)

Part 1.*

ILLUMINATION.

The object of the Lecture is to give in plain language some account of a branch of electrical engineering, of early investigations, and a sketch of scientific theories. The slow development of Faraday's work from 1821, his first primitive dynamo 10 years later, the first practicable incandescent lamp made by Swan in 1878, and the stagnation caused by the Electric Lighting Act of 1882, is contrasted with the progress made after 1888, when public electric supply became possible. The deliberate advance of elementary physical science in Faraday's time is also contrasted with the activity and complexity of modern research.

The unit on which all practical measurements of light are based is candle-power. Parliament, in its wisdom, decreed by the Metropolitan Gas Act of 1860 that the light emitted by a spermaceti candle with a special wick, six to the pound (neither length nor diameter being mentioned) and burning 120 grains of sperm per hour, should be set up as the official standard, but only for the purpose of testing London gas. The so-called Parliamentary candle has been superseded, but the unit remains. The science of measuring light dates from 1750, and is called photometry. Visual photometry consists in illuminating a white screen by the lamp to be measured, illuminating another screen by the standard lamp, and adjusting matters until the brightness of the two screens appears to be identical. The adjustment generally consists in moving one of the lamps.

When Lambert in his "Photometria," in 1770, wrote "the eye is the only judge," he regretted that the eye lacks an instrument like a thermometer so that when left to itself it might give judgment. Several attempts have been made to produce such an instrument, but there is a risk in all electrical, thermal, photographic and other chemical methods of measuring something that is not light. The recently discovered photo-electric cell is a valuable instrument of this kind.

Light is required merely to produce illumination. This consists of two factors, candle-power and distance. The practical unit by which illumination is measured is the illumination from a source of 1 candle-power received at a distance of 1 foot by a surface facing the light, and is called 1 foot-candle. Many types of instruments are in use by which illumination may be easily measured.

The subject of "glare" has received much attention from illuminating engineers. It is not a question of intensity of light, but of contrast. The head-lamps of a motor car may give a blinding glare in a country road on a dark night, but the same lamps are hardly noticeable in bright sunshine, where the eye is receiving several thousand times more light. The amount of illumination desirable for different classes of streets has been studied and is merely a matter of opinion. The results can be measured and recorded, the heights of lamps, their spacing and candle-power, and the types of lanterns can be settled and specified. Gas lighting can easily compete with this work; it is merely a question of cost. The minimum for good street-lighting is from $\frac{1}{20}$ to $\frac{1}{10}$ foot-candle on a horizontal surface midway between two lamps. In the old days, street lamps were little else than beacons to show the direction of the streets. Illuminating engineers have long lists giving the illumination which experience has shown to be necessary for various purposes. For example, at least $\frac{1}{2}$ to 1 foot-candle is needed for railway platforms and warehouses. For domestic purposes, from about 1 foot-candle in bedrooms, to 4 or 6 foot-candles for reading and working is necessary. A dining-room table is comfortably lighted at 3 or 4 foot-candles, but 12 to 15 is needed for a billiard table. The Factory Department of the Home Office has recommended certain minimum illuminations for various kinds of work; in general, 3 foot-candles for ordinary purposes, 5 for finer work, and up to 20 in special cases. Factory managers are becoming aware that accidents can be reduced, and output of production and the quality of work increased, by better lighting.

Artificial light is more yellow than daylight; in other words, it is deficient in blue and green. By suitably tinted glass the superfluous red and yellow rays may be cut off, and an imitation daylight may be produced, by which colours can be matched. Picture galleries are now lighted in this way, and "daylight" lamps are used for colour-matching, not only for textile goods, but for flour grading and other industrial purposes.

The natural daylight illumination of the interior of buildings can be measured by using a small portion of the overhead sky as a standard of comparison. At the National Physical Laboratory, experimental sheds have been erected for studying on this principle the daylight illumination of factories, offices and picture galleries.

* Part 1 of the Lecture is in abstract.

Part 2.

LIGHT.

Having got our light; what is light? This, as Dr. Hawtrey of Eton suggested to Sir John Herschell, is perhaps the oldest of all words, the first word ever

recorded to have been pronounced in the great poem of the first chapter of Genesis.

Experiments and elaborate calculations in optics were carried on through the first half of the nineteenth century, with no relation to any other branch of physics, until 1846; when it dawned on Faraday that there was an irresistible suggestion of a similarity between the lateral or side-to-side disturbances of magnetic lines of force and the vibrations of light. His view, he wrote, in a letter to his friend Phillips, "endeavours to dismiss the ether, but not the vibrations." Nothing could ever have induced Faraday to give up those lines of force which no one has ever seen, but which are the fundamental assumption of electrical science and electrical engineering.

Lay a sheet of paper over a magnet, dust some iron filings over it, tap the paper gently, and we see the filings arrange themselves along beautiful curved lines. Whether the lines are still there when we remove the iron filings, whether they really exist, or whether they are conveniences of thought, like lines of latitude and longitude, is a matter for philosophical cogitation. Faraday treated them as pure concepts. They were mere directions along which something called force acts. These lines had been known for 200 years, but it remained for Faraday to show their significance. Faraday's lines of force are in practical daily use by every theoretical electrician, and by every designer of electrical machinery.

Continental mathematicians thought in terms of imaginary magnetic and electric fluids and "action at a distance," and were slow to accept Faraday's achievement which revolutionized electrical science. But how Faraday, by abstraction, could retain his lines of force while he dismissed the ether, is difficult to understand, unless he had a vision of our present position in physical science. That he had an inkling is clear from what he wrote about infinitesimally small nuclei and almost infinitely intense elasticity. "But if," he wrote, "such be the received notion, what then is left in the ether but force and centres of force?" The rest of this letter is delightful to read in the light of the electron theory of to-day.

In 1864 Clerk Maxwell pointed out that the only electrical disturbances or vibrations that can be propagated through non-conducting space, are transverse to, or across the direction of propagation. The velocity found from experiment is so nearly that of light, that it seems we have strong reason to conclude that light itself is some kind of electromagnetic disturbance in the form of waves. "Surely," said Lord Kelvin, "we have a large and solid ground for our faith in the speculative hypothesis of an elastic luminiferous ether which constitutes the wave theory of light."

We know that sound is not a material thing. It is one of the ways in which air behaves. Light too is not a substantial thing, but according to that hypothesis consists of rapid tremors of something that has been provisionally called ether, and electricity seems not to be a thing, but the way in which something behaves.

It is generally stated that Newton held only one view about the nature of light, namely, that it consists of small particles or corpuscles, and hence the name "the corpuscular theory"; and that he did not favour the wave theory. This statement is copied from one text-book into another. But, on the contrary, his writings show that Newton gave considerable attention to the wave theory. That theory was suggested in an elementary form by Hooke in 1664. Newton, in a communication to the Royal Society in 1671, on the production of the spectrum by a prism, considers "if the rays of light should possibly be globular bodies," but he dismissed the idea and wrote, "To determine more absolutely what light is, . . . is not so easy. I shall not mingle conjectures with certainties."

Huyghens communicated his wave theory to the French Academy of Science seven years later. He dealt only with the reflection and refraction of wave-fronts, and wrote nothing on prismatic colours, wave-lengths or transverse vibrations. Newton began his Treatise on Optics in 1718 with these words: "My Design in this Book is not to explain the Properties of Light by Hypotheses, but to propose and prove them by Reason and Experiments"; and this was not the only occasion on which he declared that he was not going to make hypotheses, but failed to keep his promise. In the first edition of this treatise he dealt at considerable length with the wave theory, and there is not a word about the corpuscular theory. "Do not several sorts of rays make vibrations of several bignesses . . . do not the most refrangible rays excite the shortest vibrations for making the sensation of deep violet, the least refrangible the largest, making a sensation of deep red?" He suggested that the medium is the same as that which conveys heat, that it is exceedingly more rare and subtle than air, and exceedingly more elastic and active and pervades all bodies, and he adopted for it the name "ether" already used by Descartes, the word used by Homer for the upper pure air of the heavens as distinguished from the air in which we live, and by Aristotle for the medium in which the heavenly bodies swim.

If we look at little waves on a pond, into which a stone has been thrown, we shall see two kinds of movement. One is the steady travelling of the waves in expanding circles, the other is the no less uniform up-and-down motion of leaves or weeds that may be floating on the surface—the water does not travel with the advance of the waves, but moves up and down. The horizontal travel of the waves may be compared with the travel of light, and the up-and-down motion with the magnetic vibrations of the ether. But this is only an analogy. It must be remembered that the disturbances or alternations of condition are magnetic, and probably not mechanical at all. It is safe to say that there actually are repeated disturbances, but some authorities deny that there is an ether, and bid us think of centres of force quivering in empty space.

Towards the end of the second edition of his "Optics," Newton found a difficulty in explaining by the wave theory the colours of a soap bubble "with which children play," and apparently with reluctance he asks: "Are not the rays of light very small bodies emitted from shining substances? . . . bodies of different sizes, the least of which may make violet . . . the rest, as they are bigger and bigger may make . . . blue, green, yellow and red. . . . Nothing is more requisite for putting the Rays of Light into Fits of easy Reflection

and easy Transmission than that they be small bodies which by their attractive Powers, or some other Force, stir up Vibrations in what they act upon, which Vibrations being swifter than the Rays, overtake them successively, and agitate them so as by turns to increase and decrease their Velocities, and thereby put them into those Fits." * These words are not easy to understand, and they are almost the last words on light in this treatise. Newton seemed to be tiring of the subject, and wandered off into chemistry, and left the matter in a very unfinished state.† And now, 200 years later, the theory is still incomplete.

The electromagnetic waves of Faraday and Maxwell may be perceived by our senses directly, or by means of instruments, but only a small portion of them affect the eye. To these alone we give the name light. "Light," wrote Kelvin, "is light if you see it; it is not light if you do not see it."

When light passes through a prism, it is apparently split up or sifted into the colours of the rainbow. The expression split up is perhaps better than sifted, for many modern authorities hold that the colours are not present or have no independent existence before the ray of light enters the prism. The visible part of the spectrum occupies only about one octave; that is to say, there are about twice as many vibrations per second in violet light as there are in red light. The length of the waves for different colours may be measured with great precision, and are known and definite. The wave-length at the red end is about 30 millionths of an inch,‡ and at the violet end, about 15½ millionths. The velocity of light, 186 300 miles per second, is known, and therefore the number of vibrations; for example, 500 million millions per second in the yellow, though they cannot be counted, may be calculated. Beyond the red end of the spectrum are about 6 octaves of invisible heat rays, but waves longer than about 50 millionths of an inch are stopped by glass; it is opaque to them. Until quite recently there was a gap here of about 10 octaves, but this has now been filled, partly by detection of heat rays, and partly by electrical methods. This brings us to wave-lengths of a few inches. These were detected electrically by Hertz in 1888, and are used for radio-telegraphy and radio-telephony. These waves are of such convenient dimensions, so easily produced and detected, that it is in this region we may look for the discovery of the true nature of a light wave. It will probably turn out to be an electrician's investigation. Eight octaves more and we come to waves used for ordinary broadcasting. Those sent from the Eiffel Tower are about 1 mile 5 furlongs in length, about 20 octaves from the visible spectrum.

Exploring in the other direction, beyond the violet end of the spectrum, there is about an octave of rays called ultra-violet rays. The shortest waves of sunlight are about 11½ millionths of an inch. In moderation they are beneficial, they tan the skin, and have certain healing properties, and powerful photographic action. Beyond these are other ultra-violet rays such as those emitted from a mercury-vapour lamp; they may be dangerous. Far beyond these again are about 14 octaves, the X-rays discovered by Röntgen, a few hundredths of a millionth of an inch in length. In all, about 50 or 60 octaves.

The total radiation from an ordinary candle flame consists of about 999 parts of radiant heat to one part of light. From an electric glow lamp the radiation is about 3½ per cent, or, as Prof. Houston puts it, in £3 worth of energy there is £2 18s. of dark heat, and 2s. worth of light. A gas-filled (or so-called "half watt") electric lamp gives 7 per cent, and an open arc gives about 10 per cent.

The secret of producing light without heat is known only to the glow-worm and the firefly. They have been severely examined about this, but as yet they have declined to give any explanation of their behaviour.

So far as is known, I repeat, all these vibrations and disturbances are of the same nature. From the X-rays comparable in size with atoms, to the longest waves used in wireless telegraphy, they consist of simultaneous magnetic tremors or vibrations at right angles to each other, and advancing in a direction at right angles to both. The apparent difference between them lies in the means at our disposal for detecting them. From the X-rays, down to the red end of the spectrum and a little further, photography is used, overlapping that part which affects the eye. Below this, measurements of radiant heat are made, and lastly the vibrations are so slow that they can be detected electrically. Those are used for broadcasting, and vibrate between ½ million and 1 million times per second.

The Ether.

Vibrations; but of what? Ether, the name of a medium which has been held to be that which transmits light, is not an observed fact. It still remains, as Lord Kelvin said, a speçulative hypothesis, and it does so because it remains a conception. Vibrations have been observed, and all that was asked of the ether was that it should vibrate. It was assumed that it has inertia or mass, and is elastic. But it has never been observed, because it has absolutely unbroken continuity.

The old thinkers had a dogma—"Nature abhors a vacuum." This had troubled Descartes in the seventeenth century. He thought that two bodies must be either touching each other, or separated. If they were obviously separated, and all known substances between them were removed, and they still remained separated, there must be something left. For this unknown he

* About twelve pages of the second edition are devoted to "Fits of easy Reflection and Fits of easy Transmission"; eight pages to the undulatory theory and ether, and only about two pages to the corpuscular theory.

† The reason why Newton is generally supposed to have advocated the corpuscular, and rejected the undulatory theory of light is, that a controversy arose in which his followers supported the corpuscular theory, and the dispute became so acute that Newton, in a letter of 1675, wrote: "I was so persecuted with discussions arising out of my theory of light, that I blamed my own imprudence for parting with so substantial a blessing as my quiet, to run after a shadow." A year later · "For I see a man must either resolve to put out nothing new, or to become a slave to defend it." May we not read between the lines that he was not satisfied with his corpuscles?

So late as 1827, Sir John Herschell, in his article on Light in the "Encyclopædia Metropolitana," devotes ten pages to the corpuscular theory, with which he appeared fairly satisfied, and seven to the undulatory theory, of which "we may almost be induced to say, if it be not true, it deserves to be so."

‡ The expert will criticize the vulgarity of these fractions. There is still a great deal of confusion in expressing wave-lengths in decimals on the metric system. To-day, the tendency is to express them in Ångström Units (Å.U.). One Å.U. is the length of 1 ten-millionth of a millimetre. The wave-length of one of the well-marked lines in the yellow part of the spectrum is 5 895 Å.U. Another unit is the milli-micron or micro-millimetre ($\mu\mu$). It is 1 hundred-thousandth of a millimetre, and equal to 10 Å.U. A micron (μ) used in other branches of science is 1 thousandth of a millimetre, or 10 000 Å.U. One-thousandth of an inch is 254 000 Å.U.

adopted the name "ether." It had not much to do. But others were invented by philosophers, and space at last became filled with ethers several times over. Newton's form of the undulatory theory led him to two simultaneous ethers, and he rejected the idea as inconceivable. "To fill all space with a medium," wrote Maxwell, "whenever a new phenomenon is to be explained, is by no means philosophical." This was his apology for inventing one ether which would account for electromagnetism as well as for light. But a great deal was expected of this ether when it came to be examined, and many attempts have been made to imagine a structure which would account for the properties that it ought to have. The great mistake seems to have been in treating ether as matter or a kind of matter. In 1845, Prof. Stokes taught that it was a kind of jelly, and made brave attempts to reconcile some of the apparent contradictions involved. Then Kelvin and Helmholtz showed how it might consist of spinning vortex-rings like smoke-rings, having a rigidity like that of a top; and in 1889 Sir Oliver Lodge seemed to suggest that the universe was full of cog wheels. These ethers and a score of others are buried for the present in obsolete books. It is possible that more may be heard of them.

The ether has always been an imaginary medium. It has defied all experimental attempts to observe it, unless some recent experiments in America are to be accepted in this connection. We have knowledge of it neither by description nor by acquaintance. Light takes about 8 minutes to pass from the sun to us. What is it doing on its journey? The difficulty is to understand how light and electromagnetism are to be accounted for if the ether is abolished. It is admitted by our leading mathematicians that Maxwell's six equations expressing the electromagnetic theory are identical with the latest mathematical theory; but to put it into plain language has baffled every one of them. That is not the business of mathematicians. They are content with their equations, and some of them do not care whether there is an ether or not.

It is easy to say that light consists of tremors at right angles to the direction of travel. We have plenty of names for them—waves, vibrations, tremors, quivers, undulations and so on—but we want to know more about them. These names suggest a motion of the medium, but, as I have said, the alterations are probably only magnetic, and we know of them only in one dimension at present—the wave-length.

Although Einstein says that he has no objection to the ether, his system being independent of it, some of his followers say that the hypothesis of an ether is useless, unwarranted, and unnecessary. But most of those of us who have listened to Sir Oliver Lodge's broadcast lectures on "Ether and Reality," or have read his recent books on the subject, probably feel that the ether is not to be dismissed by a summary negation. He says that it is the only reality in the universe, and distinctly holds that it is not matter.

The Quantum Theory.

It is agreed that all matter is composed of minute atoms, and these again are formed of vastly smaller particles called electrons, swiftly revolving like planets round a central nucleus. To pass from the idea of a charged nucleus to a centre of force without a nucleus presents no difficulty to the mathematical mind; but to the constructive mind it is like the grin without the Cheshire cat. Electrons vary in number in different kinds of atoms, and each electron has a stable orbit in which it revolves. But there is a choice of orbits. An electron can change its orbit under suitable compulsion, but the remarkable and unexplained thing is that it does not do so, as one might expect, by taking a smooth spiral path. The rule that Newton adopted for Nature, that she must never act in leaps, has been broken, and an electron if driven from its orbit may fly outwards, or it may drop inwards towards the nucleus. When jostled out of its orbit, say by heat, raising matter to incandescence, an electron drops suddenly into a smaller orbit of higher velocity (that it should do so instantaneously is unthinkable) and, in doing so, liberates a definite and limited amount of radiant action. This is called a quantum. There is a mysterious limitation in the amount of energy so set free. The magnitude of a quantum, measured as the product of energy and time, has been estimated, and numerical results converging from different branches of physics agree; and its magnitude is what we know most about it. Calculations show that about 10 per cent of hitherto unexplained features in the structure of the spectrum and of interference and diffraction of light are thus accounted for, besides many other physical facts: but the remaining 90 per cent cannot be so explained, and appear to be fully accounted for by the ordinary wave theory of light. It must not be deduced that the voting is 10 to 1 against the quantum theory. Not at all. This discordance must be puzzled out and settled.

It has been suggested that a quantum becomes, for all intents and purposes, a materialized body; the crude expression "granules of energy" has been used, and on this has been founded the sensational statement that we must return to the corpuscular theory. It may be that there is no discontinuity in the flow of radiation, but that it must accumulate to a certain quantity before matter can react to it. Matter may have to be re-defined. The fact is, that our ideas both of energy and matter are in the melting pot, and we must wait until they have been tried by the fire of mathematical analysis in the crucible of philosophy. Meanwhile we may take it that there is nothing seriously wrong with the wave theory of light, as far as it has been developed, but a complete theory has not yet been formulated by our physicists and mathematicians.

A constructive theory of the physical nature of a wave of light has been long overdue. Sir Joseph Thomson has recently made a proposal about the structure of light. He suggests that when an electron jumps from one orbit to another, the lines of force joining the electron and the nucleus snap and become a ring of force, which carries nearly all the energy. The formation of the ring of force sets it into vibration and gives rise to electromagnetic waves. Such rings of force travelling at the speed of light, according to this hypothesis, are quanta. This interesting suggestion was stated in plain language without reference to the ether, to relativity,

or to obscure metaphysics, but it unfortunately presents no mental picture whatever of the structure of an undulation of radiant energy, or what is going on in a wave front. The theory is surely coming; it may appear any day.

In any form of the corpuscular theory, whether that of Newton or that of the quantum, the velocity of propagation is not that of a projectile to which an acceleration or push has been imparted, but it has something to do with the nature of the space traversed, whether the name "ether" is given to it or not. This is evident from the undisputed fact that the velocity of the train of waves is reduced while light is passing through glass, but the original velocity is exactly resumed when the light emerges. Call it what we will, this appears to me to be one of the strongest proofs of the existence of a medium.

Much of the confusion which we find at the present time in physical science is due to the inadequacy of words to express exact thought. Language is apt to assert more than we mean it to assert. There is "a tyranny of words." Writers on the difficult subject of relativity, which ought to be a clue and not a maze, evolve new ideas and, instead of coining new words to express them, as any chemist, botanist, or zoologist would do, borrow from ordinary language such common words as space, action, interval and world, and apply them to new, special and intricate uses.

Mathematics.

Simple problems may be treated by experiment, or by geometrical diagrams, or by analytical mathematics, but the most recent researches can be presented only in advanced mathematical language, often mixed with metaphysics, and, like the theory of relativity, cannot be put into plain words.

We may say: If it cannot be put into words, how can it affect me or my life? But take the case of music. A simple tune or air can be expressed in the usual musical notation, or on the Tonic Sol-fa system, or it may be played on a musical instrument, or it may be sung, whistled or hummed. But it cannot be put into words. A journalist critic who could write a column about a song could not describe or express the tune in words.

Physics describes what we observe, and offers an explanation. Mathematical metaphysics discusses what we imagine, and offers us an assertion. Pure mathematics must not be confused with applied mathematics. The pure mathematician may arrive at a theorem or an expression without any bearing on physical reality and without intending that it should have any such bearing. Some of their creations " exist only in virtue of their definitions." To make any progress in the new physics without higher mathematics is quite impossible. But that science is utterly unintelligible to those who are not mathematicians. We must not blame the mathematicians. Mathematics is a highly condensed form of logical reasoning, making it easier to think. In the fourth century before algebra was invented, the mathematical problems of those days were solved by a process of reasoning expressed in words, without the use of any symbols. Mathematicians, like some poets, write for each other: outsiders are not expected to understand. "But," as Sir Oliver Lodge says, "the end is not yet, and we shall come out into common sense later on. . . . The human mind is not a constructor of nature—only an interpreter."

Relativists appear to be annoyed with the ether hypothesis because it reminds them of the jelly and vortex-ring analogies, which appear to them crude and mechanical compared with their elegant mathematical work. But is not this merely quarrelling about a name? Some of them admit that there is a "universal substratum of things," others, that there is such a thing as "space" or a "four-fold extension" endowed with physical properties.

To endow empty space with physical properties in order to explain observed facts, seems rather like insisting that water flows because it has the property of aquosity, or that a clock keeps time because it has the property of horologity.

It is all very well for the mathematical metaphysicist to say that he has no use for the ether because it does not appear in his equations. If we want to adopt the wave theory of light, we may frankly admit that our medium is a product of our imagination. It will do as a peg on which to hang the theory. We cannot, like Saint Bridgid, hang our cloak upon a sunbeam; we leave that to brilliant mathematicians.

And here, after behaving like an electron, in skipping about from one topic to another, I must leave the theory of light in an incomplete state. But I have taken up time with a discussion on undulations or vibrations without giving any tangible idea or the vaguest mental picture of what such an undulation is like. So far as I know, no physicist or mathematician has been able to describe it in anything but mathematical terms. We need another Faraday.

I have tried to give a short account of the history of electric lighting, of the simple but important problems of the art of intelligently using light for domestic and industrial purposes, and have attempted to give a sketch of the present position of the theory of light. I hope that some of my audience will wish to know more, and that all of them, even those to whom science has little attraction, will wish to become further acquainted with the life and personal character of the great and good man, Michael Faraday, in whose honour this lecture has been given.

SOME PROBLEMS OF THE TURBO-ALTERNATOR.*

By E. GALLIZIA, Student.

(*Paper read before the* SOUTH MIDLAND STUDENTS' SECTION, *7th April*, 1925.)

SUMMARY.

The paper deals with some of the problems that the designer has to face which are seldom dealt with in treatises on design, and for this reason have been dealt with in detail.

The paper is divided into sections as follows :—

1. *General.*
2. *Materials.*

   (*a*) Stator.
   (*b*) Rotor.

3. *Tests for flaws.*—The following methods are dealt with :—

   (*a*) Clink detection.
   (*b*) Optical tests.
   (*c*) Chemical tests.
   (*d*) Overspeed test.
   (*e*) X-rays.
   (*f*) A successful potential-drop test developed by the G.E.C. Development Department. The results are published for the first time.

4. *Mechanical design.*—This is considered from the point of view of the variation of the strength of the forging with radial depth and the efficiency of ventilation. Wedges and end-bell stresses, factor of safety, methods of test, and the available materials are dealt with. In the case of the rotor the best methods of determining the strength of the steel at the tooth root are fully discussed and methods of improving the strength of rotor forgings generally are suggested.

5. *Ventilation and liquid cooling.*—Comparison is made between :—

   (*a*) Liquid and air cooling.
   (*b*) Wet and dry air filters and closed air systems.
   (*c*) High-speed and low-speed separately driven fans.

Results of experiments on the effect of core spacers and wedges on volume and pressure of air are given.

6. *Insulation and temperature distribution.*

   (*a*) Measurement of temperature by thermo-couples.
   (*b*) Recommended methods of insulating.
   (*c*) Maximum temperatures.

7. *Balancing.*—A method is suggested whereby it is possible to move the balance weight at full speed. This may be worth while developing.

1. GENERAL.

Owing to the exacting demands on the mechanical design in addition to the electrical requirements, the turbo-alternator presents a considerable number of interesting problems, a few of which will be dealt with in this paper.

Mistakes in the electrical design may cause considerable loss of time and money, but any mechanical defects may be disastrous, resulting in loss of life.

The turbo-alternator has of course been primarily developed in order to make use of the steam turbine with its comparatively high efficiency, which increases with both the output and velocity, particularly with regard to the latter. It can be shown that the blade velocity should be of the same order as the steam velocity, which, with the high vacuum now obtained, is exceedingly high.

Apart from the above considerations, the development of the turbo-alternator is not justified, when compared with the low-speed alternator. It is less efficient, and it cannot show a lower first cost or greater reliability. The low-speed alternator of 750 r.p.m. coupled to a 5 000–6 000 r.p.m. turbine by means of reduction gearing at present only offers an attractive proposition in a size of 1 000–5 000 kW, but considerable improvement on the gearing is continually being made.

It is only during the past few years that the electrical designer has been able to produce machines of the size demanded by the turbine builder and now the position threatens to become reversed, owing to the large volumes of steam which have to be dealt with in the last stage at the high vacuum now used. This necessitates increasing the ratio of steam velocity to blade velocity considerably above its theoretical value, and so raising the leaving losses which form a considerable proportion of the total energy. In addition, the difficulties increase as the temperature and pressure increase, owing to the large drop in pressure and temperature in one single casing.

Units of 45 000 kVA at 1 800 r.p.m. and 25 000 kVA at 3 000 r.p.m. can be built, and units of greater capacity would not be used except in the case of the very largest stations. Owing to the present system of interconnection, five units per station would appear to suffice, although seven are probably better. This allows five working machines, one spare machine and one for overhauling.

The characteristic features of the turbo-alternator are :—

(1) High peripheral speed up to 475 ft. per sec. (28 500 ft. per min.).
(2) High bearing speeds up to 130 ft. per min.
(3) Great axial length of core.
(4) Great radial depth of stator core.
(5) Large air-gap.
(6) Large coil span, particularly with the large 25-cycle, 2-pole machines.
(7) Concentration of large losses in small volume, resulting in high temperature gradients.

* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

In addition, the designer is considerably handicapped by the fact that it is only possible to carry out tests on site, and then not of an experimental nature.

Owing to the comparatively high efficiency of 96 per cent in the case of large alternators compared with 30 per cent overall, future development should be considered in the following order of precedence.

(1) Reliability.
(2) Efficiency.
(3) Ease of operation, and first cost.

Reliability and efficiency, however, are very difficult to distinguish, because higher efficiency, which means lower losses, immediately results in a more reliable machine. It is because of such losses, approaching 1 500 kW in the largest machines, that the stator core and rotor have to be of comparatively flimsy construction in order to provide suitable air paths for carrying away the resultant heat.

The number of alternators developing faults from all causes, in both stator and rotor, appears to be about 8 per cent of the total. In many individual stations the figure is much lower, whilst Glasgow appears to have been exceptionally unfortunate, 16 machines having failed out of a total of 21, i.e. 76 per cent. There still remains, therefore, considerable room for improvements as regards reliability. Considerable improvement has already been made in the reduction of the weight and floor space; a steam turbine and alternator would require a floor space of the order of 35 sq. ft. per 1 000 kW and would have a weight of approximately 15 tons per 1 000 kW.

Although the electrical design is very closely related to the mechanical design, resulting usually in a compromise between the two, practically no mention will be made in the paper of the design of the electrical and magnetic circuits, as a considerable amount of literature is available on these points. Such literature, however, usually ignores the difficulties encountered by the manufacturer.

The most important variation in the stator design lies in the system of ventilation adopted and in the type of winding used to reduce as far as possible the eddy-current loss. The rotor design, however, falls into three very distinct classes, two of which are extensively used. The first is the solid forging (original Brown-Boveri) from which the radial slots are milled; the second is the plate (or disc) or built-up rotor, consisting of a shaft on to which the plates with stamped-out radial slots are built. The third is the Hungarian practice * in the 2-pole design, in which the rotor is built up in three sections. The central portion, to which are finally bolted the two shaft-ends, has parallel slots (not radial) which are continued round the ends of the cylindrical body. With this design the chief advantage, amongst others, is that it is unnecessary to use support rings. There are, however, a number of obvious disadvantages, although 160 of these 2-pole machines have been built with very successful results. The largest is a 3 000 r.p.m., 15 500 kVA machine.

* E. Wilczek: "Hungarian Practice in High-Speed Turbo-Alternator Design": paper read before Section G of the First World Power Conference, July 4, 1924.

The large number of solid and built-up rotors in operation is sufficient evidence that both types give satisfactory results, but it may be said in general that the stresses in the built-up rotor are undoubtedly higher, and that greater difficulty is experienced with critical speeds, but it has a considerable advantage from the point of view of ventilation and the fact that each small section can be fully examined for the presence of faulty material.

The latter is perhaps its greatest point, but, having obtained a sound forging for the solid rotor type, there is no doubt that it is the better engineering construction.

The methods adopted for ascertaining the soundness of the solid rotor forging forms one of the problems to be dealt with in this paper.

2. Materials.

(*a*) *Stator frame.*—The stator frame is generally made in a single casting of grey iron of comparatively massive box section, the ribs of which form suitable compartments for the particular type of ventilation adopted. For the largest sizes of alternators, where there may be transport difficulties, a comparatively light steel frame built up of **I** sections can be used. Wherever possible it is preferable to use a single casting which is accurately bored to take the laminations and suitably machined for the fixing of the core-plate keys. The stresses even under short-circuit conditions are comparatively small, and the most important consideration in the design is that of preventing contraction stresses by suitably proportioning the various parts. The resulting casting should be easy to machine, reasonably free from blow-holes, and have a comparatively smooth surface, both externally and in the air chambers.

The analysis of a suitable grey iron for the stator frame is as follows:—

	per cent
Total carbon	3·5
Graphitic carbon	0·5
Combined carbon	3·0
Silicon	2·0
Sulphur	0·05
Phosphorus	1·0
Manganese	0·4

A suitable specification, with which the above iron would comply under correct casting conditions, is as follows:—

Tensile strength, not less than 10 tons/sq. in.
Compression strength, not less than 45 tons/sq. in.
(Sample 1 in. diameter by 2 in. high.)
Brinell hardness (3 000 kg, 10 mm ball), 190.

Transverse test.—A 1 in. square bar, 14 in. long, cast with the stator frame, when placed on knife-edges 12 in. apart must support a load of 2 000 lb. at its centre and give a deflection of not less than 0·12 in. without fracturing.

(*b*) *Rotor.*

(i) *Plate.*—Carbon-steel plates (14 S.W.G.) having the following tensile properties can be easily obtained for built-up rotors:—

	With rolling	Across rolling
Yield point, tons/sq. in. ..	24·0	25·5
Maximum stress, tons/sq. in. ..	35·0	36·5
Elongation in 8 in., per cent ..	18·0	16·0
Scleroscope hardness	26–27	26–27

(ii) *Solid.*—It is not essential to know the steel maker's procedure in procuring suitable molten steel in the ladle ready for teeming, but from that point onwards it is necessary, when discussing the mechanical properties of the resultant forging or the possibility of the presence of flaws, to know the essentials of the process.

The mould is usually made of cast iron and is a cone of octagonal shape, as shown in Fig. 3, the circular mould, contrary to expectation, not giving such good results.

Fig. 1 shows a section through an ingot to which no silicon or aluminium has been added as a deoxidizer, whilst Fig. 2 shows the results after the addition of 2 oz. of aluminium per ton. In the first case the contraction cavities are comparatively small but numerous, with the result that a large proportion of the ingot is

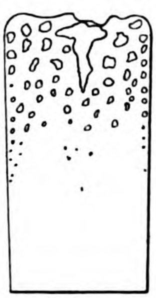

FIG. 1.—Ingot without the addition of a deoxidizer such as aluminium or silicon.

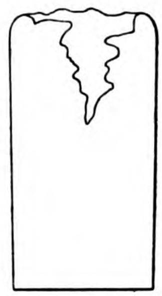

FIG. 2.—Ingot to which 2 oz. of aluminium per ton have been added.

useless. In the second case there is a large single cavity (piping) which also results in a large percentage of scrap.

The production of sound forgings having suitable characteristics requires the correct combination of a large number of factors such as pouring temperature, analysis, rate of cooling, etc., and the effect of very small percentages of aluminium is mentioned as an example. Full deoxidation cannot, however, be obtained by the use of aluminium alone, the presence of a definite proportion of manganese being necessary. Under no circumstances therefore should a definite analysis be specified in conjunction with the physical properties, but a free hand must be given to the forge master. The analysis of the steel is only of importance to the designer in so far as it affects to some extent the magnetic characteristics.

The problem which has confronted the steel maker is that of eliminating cavities, and various means have been adopted in order to produce sound ingots. One such method is to use the inverted mould shaped as shown in Fig. 3, in which the steel solidifies from the bottom to the top and from the sides radially inwards. If a steel giving only a single large contraction cavity when cooling freely is kept heated at the top whilst the remainder of the ingot solidifies, it is possible to obtain a uniform ingot.

As shown in Fig. 4, the mould is provided with a "head" which is kept hot by means of sand, slag and charcoal. The head of the ingot is finally scrapped, as a considerable segregation of carbon, sulphur, etc., takes place at this point.

As far back as 1878, Prof. D. R. Tschernoff read a paper before the Russian Technical Society dealing with segregation, blow-holes and piping in cast ingots,* whilst in 1881 Mr. Stubbs, in the discussion on a paper by Mr. John Parry (*Journal of the Iron and Steel Institute*, 1881, p. 200), pointed out that considerable segregation did occur, as he had found that an ingot 90 in. long gave a carbon content of 0·92 per cent at the top and 0·37 per cent at 30 in. from the bottom. Mr. G. T. Snelus rather discredited that such segregation did take place, but he immediately put in hand tests which proved the correctness of Mr. Stubbs's statement.

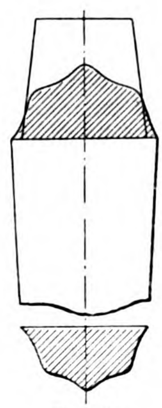

FIG. 3.

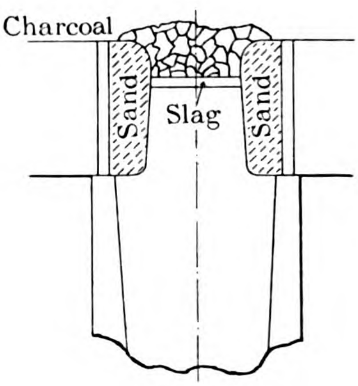

FIG. 4.

The test consisted of casting an ingot 19 in. square and 7 ft. long, having purposely high impurities, and prolonging the rate of cooling so that the ingot was not properly cold two days after casting. An analysis was made with the following results :—

	21 in. from top	4 in. from bottom
	per cent	per cent
Carbon	0·76	0·35
Silicon	Trace	Trace
Sulphur	0·187	0·044
Phosphorus	0·191	0·044
Manganese	0·558	0·514

In addition, six equi-spaced samples were taken, travelling diagonally from the corner to the centre of

* *Proceedings of the Institution of Mechanical Engineers*, 1880, p. 152.

the ingot, some of the results of which are given below :—

	Top		Bottom	
	Corner	Centre	Corner	Centre
	per cent	per cent	per cent	per cent
Carbon	0·44	0·77	0·44	0·37
Sulphur	0·032	0·187	0·048	0·044
Phosphorus ..	0·044	0·142	0·060	0·052

It will be seen that serious segregation of carbon, sulphur and phosphorus had taken place. Such variations are, of course, not normally obtained, but the figures are given to show that the possibility of segregation taking place is always present in very large forgings. Large ingots for rotor forgings may show a carbon content of 0·26 per cent at the bottom and 0·40 per cent at the top. The core of a large forging is always of poor quality, and it is in this region that cavities normally exist. It is therefore always advisable, apart from considerations of heat treatment, to bore the forging for examination, as explained in Section 3.

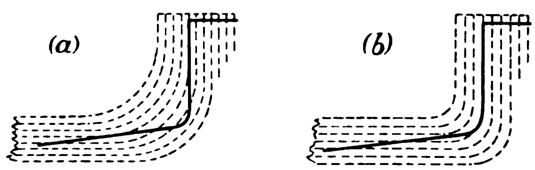

FIG. 5.
(a) Radius of forging tool too large.
(b) Radius of tool correct.

It is important that sound ingots of uniform and correct composition be obtained, as no amount of forging or heat treatment will bring out qualities which do not exist in the steel. The usual procedure is to take an ingot 30 per cent larger in diameter than the final forging and to commence forging down at a bright red heat. Care has to be taken that the temperature does not fall too low, owing to the possibility of producing flaws, especially at a marked change in section. Normally 5 per cent from the bottom and 35 per cent from the top of the ingot is discarded, so that for a 35-ton forging an ingot weighing about 55 tons is required.

At marked changes in section the radius of the forging tool should preferably approximate to that of the final machining, as indicated by Fig. 5 (*b*), where the dotted lines indicate the grain of the steel and the full lines the final machining. It will be seen in Fig. 5 (*a*) that with a forging tool of large radius a large number of fibres are finally cut through, constituting a point of weakness where the stresses, both dynamic and static, are greatest. This, however, is not always possible or advisable, as for example in the case of alloy-steel forgings which are oil-hardened. In such forgings the change in section should be made by a number of comparatively small uniform steps in order to prevent the possibility of fracture during subsequent heat treatment.

Normally the chance of a cavity being welded up by forging is extremely remote, and it is more likely that its area will increase, due to the flow of steel. In general, it may be said that forging raises the tensile strength of the outer shell of a good ingot, but it will not make a bad ingot into a good forging.

Wherever possible, oil-hardening is resorted to in order to obtain the maximum strength consistent with such large forgings, followed by normalizing in order to remove any stresses set up during forging and subsequent heat treatment. Rotors of 35 in. and upwards in diameter may be oil-hardened, provided that they are suitably bored.

It is usual for rotor forgings to be made from a carbon steel having the following approximate analysis :—

	per cent
Carbon	0·4
Silicon	0·15
Sulphur	0·03
Phosphorus	0·03
Manganese	0·7

The phosphorus and sulphur should not exceed 0·05 per cent, as segregation of these two impurities rapidly reduces the tensile properties of the steel. A steel of the above analysis forges well and is very reliable as regards the absence of clinks, segregation and similar defects, and in addition it gives a reasonable tensile strength when air-cooled and normalized. The strength may be considerably increased by oil-hardening, but the steel is said to be "strained," the elongation and contraction being considerably reduced. For this reason, where the stresses are high, as in the case of 15 000–20 000 kVA, 3 000-r.p.m. machines, it is necessary to use a 3·5 per cent nickel steel with about 0·3 per cent carbon, even though it is more difficult to ensure a sound forging.

As regards the magnetic properties, which of course are very important, a 3·5 per cent nickel, 0·3 per cent carbon steel is slightly better when both steels are in the condition in which they are normally used for turbo rotor forgings. Characteristic figures are given below :—

H	Density B in lines per cm²	
	0·4 per cent carbon	0·3 per cent carbon, 3·5 per cent nickel
10	8 300	9 900
100	16 700	17 450
2 500	22 650	23 200

3. TESTS FOR FLAWS.

As already pointed out, the greatest disadvantage of the solid forging is the possibility of the presence of undetected flaws which may not produce failure until after a considerable period of running, and the methods adopted for ensuring the soundness of forgings will now be considered.

(*a*) *Clink detection.*—Owing to the large masses involved, heating and cooling processes are often accompanied by severe stresses which have resulted in the internal fracture of the forging, followed by a loud

ringing report which has given the necessary warning. Cases have, however, occurred where either the fracture has not been accompanied by a report or there has been no one in the vicinity at the time. Recently an account * was given of a clink detector for steel ingots and forgings developed by C. A. Parsons and Co. in conjunction with the Cambridge Instrument Co. The vibration set up by the fracture of the forging is made use of in this instrument, which is really a vibration recorder, consisting essentially of the detecting instrument, which is placed on the forging, and the clock-driven time recorder. The detecting instrument consists of a horizontal spring contact carrying at its end a brass weight which, due to its inertia, produces a lag in the travel of the spring, thereby actuating the contact, the operation of which is recorded on the chart. Periodic hammer blows are given to the forging in order to test the apparatus.

(*b*) *Optical tests.*—Immediately the rotor has been bored and the borings have been examined, the optical examination should be made while the bored surface is still bright. This may be carried out in several ways, one of which consists of using a steel periscope tube about 12 ft. long and $1\frac{1}{2}$ in. diameter. Such a tube would carry at one end the eye-piece and at the other a mirror and a small 4-volt lamp, producing the necessary illumination.

Lenses would be arranged to give an apparent magnification of about $1\frac{1}{2}$ times to twice full size. The actual magnification is, of course, greater, as the surface is observed at a distance of 12 ft. Higher magnification should be provided for the examination of doubtful places, The test consists in moving the tube axially and circumferentially and scrutinizing every portion of the bore.

Where heat treatment is carried out after the preliminary boring, followed by "finish boring," the test should be repeated. All doubtful places should be polished by means of grinding and polishing bobs carried on the end of a shaft running in bearings supported by the bore and driven at the opposite end by means of a small motor.

The optical examination of the external surface needs little comment, except that it should be carried out immediately after slotting and turning and preferably again after several days, as fine hair lines have been known to show only after exposure to the atmosphere, whereas often they are more pronounced on a clean surface.

(*c*) *Chemical tests.*—Chemical tests are only applicable to surface investigation and consist of etching and the making of sulphur prints from surfaces prepared by polishing. Very fine cracks are often difficult to detect, and etching by means of a 20 per cent solution of nitric acid is often resorted to in order to produce contrast by staining.

Sulphur prints are generally taken by the method suggested by Baumann. This consists of soaking for a few moments a matt silver bromide photographic printing paper in a dilute (3 per cent) solution of H_2SO_4 and then pressing the sensitized side on to the metal surface for one minute. The H_2SO_4 attacks the sulphides, liberating hydrogen sulphide, which in turn reacts on the silver bromide and selectively darkens it, depending on the concentration of the sulphur. The paper is then washed in water and fixed in the ordinary way by a 20 per cent solution of sodium hyposulphite.

* *Engineering*, 1924, vol. 118, p. 658.

Silver salts are also affected by phosphine and are liable to record the presence of phosphide, and from that point of view the method originally suggested by Prof. Heyn, of using strips of silk impregnated with mercury chloride (mercury salt being unaffected by phosphine), is correct for sulphur printing. In practice it is found that the effect of the phosphides on silver bromide paper during the period of one minute normally employed is generally small and in any case the sulphides and phosphides are both harmful and are generally found together, so that from the point of view of the detection of segregation the Baumann method is satisfactory. (Lantern slides shown by the author brought out the sensitivity of the method in distinguishing between good and bad material.)

(*d*) *Overspeed test.*—The overspeed test, which has to be carried out in a "bomb-proof" chamber, is applied to the rotor and end bells, but particularly to the rotor. The test is carried out before winding, with the result that the overspeed necessary to obtain stresses higher than those reached with the normal 15 per cent overspeed is in the region of 50 per cent, i.e. a 3 000-r.p.m. machine would have to be run in the neighbourhood of 4 500 r.p.m. One Continental firm is reputed to carry out this test at a temperature of about 150° C. by means of a steam jacket, and the test then becomes an expensive and elaborate one. There is, for instance, the high bearing speed, which would make it difficult to continue the test for any length of time. This test, in the author's opinion, is not justified and in fact may be detrimental.

It is possible that a rotor having a small flaw may be stressed to an extent sufficient to weaken it further and yet not produce total failure. It may then happen that after one or two years' service, owing to the continual vibration the flaw may grow to the extent of producing complete failure, whereas if no overstressing had occurred during the overspeed test this progressive failure might not have been started.

(*e*) *X-rays.*—So far it has not been possible to apply X-rays to the examination of turbo rotor forgings, owing to the comparatively small depth of penetration at present obtainable. Even should the penetration be considerably increased, it would be very difficult to apply the rays so as to test the radial thickness of the forging, owing to the small size of bore which, for the very largest rotors, cannot be made very much greater than 6 in. in diameter, on account of limitations of (*a*) maximum bearing speeds of about 130 ft. per sec., which limit the external diameter, (*b*) the methods used for carrying the exciter, and (*c*) the coupling bore.

The alternative is to test along the diameter, and this, even in the smallest rotors, would require a penetration of about 26 in.

The present practical limits of penetration are:—

Lead	0·2 in. (approx.)
Carbon steel	3·0 in. (approx.) *
Aluminium	6·0 in. (approx.)

* Mr. A. E. Bullin, Director of the Radiological Institute, Woolwich, stated in the last Cantor Lecture given before the Royal Society of Arts that he has recently been able to increase the penetration of steel from 3 in. to 4 in.

The penetration of 3 in. of steel requires a tube absorbing 3·0 mA at 200 000 volts. One inch of steel can be radiographed by means of a tube absorbing a few milliamperes at 140 000 volts with an exposure of one minute, whilst with present screen sensitivities only about 0·2 in. can be examined satisfactorily.

Statements have been made from time to time that owing to the physical conditions very great penetrations cannot be obtained, and Mr. A. G. Warren deals * fully with this point, stating that the conclusions have been based on incorrect data. Taking present practical results and the latest research data, he gives a set of curves (reproduced in Fig. 6) as representing the

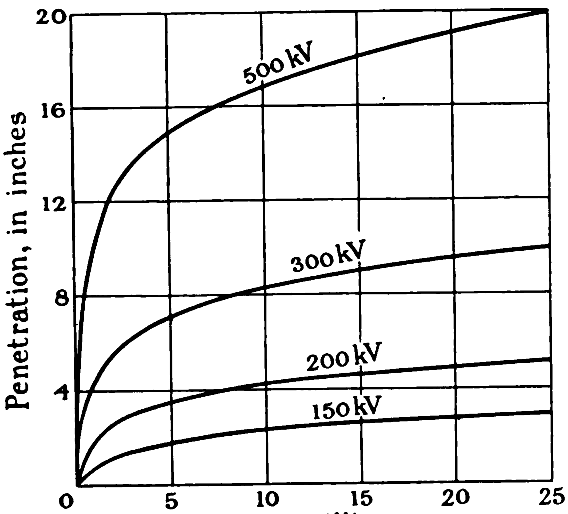

FIG. 6.

penetration which it is physically possible to attain with increasing X-ray outputs.

The predicted curves are made with some reserve owing to indefinite experimental data, particularly with reference to the variation of the mass absorption coefficient with heavier elements and high-frequency radiations. It will be seen that a tube absorbing 25 mA at 500 000 volts is predicted as being capable of penetrating 20 in. of steel, but even this is insufficient for the examination of rotor forgings. The ultimate solution of such deep penetration will probably require metal tubes capable of dealing with anything up to 40 kW, and the complete apparatus with high-tension electrical plant will undoubtedly be very expensive.

X-rays can, however, be satisfactorily used for the examination of such parts as turbine wheels, but as regards the turbo-alternator the most useful field appears to be the examination of the support rings. The process is a long one owing to the small area which can be examined at one instant and the time required for the exposure, the support rings being anything up to 2½ in. thick, 2 ft. axial length and 5 ft. diameter. In addition, an expert is required who must not only be fully conversant with X-ray technique but who, having obtained satisfactory radiographs, is able to interpret the results. This is by no means easy, owing to the sensitivity of the rays to tool marks, surface blemishes and variations in chemical composition. The test is an expensive one, but the rings, owing to their importance, should be X-rayed unless the potential-drop test has been applied, in addition to the chemical tests, such as sulphur printing and etching.

(*f*) *Potential-drop method.*—From the account given of the above 5 tests, it will be seen that no really satisfactory method exists (so far as the author is aware, except the test to be described) of finding deep-seated flaws unless they show up during the optical bore test.

A potential-drop test was developed some years ago by the General Electric Co.'s Development Department after a considerable amount of experimental work. A number of methods were suggested, such as the frequency of sound waves and their rate of travel,

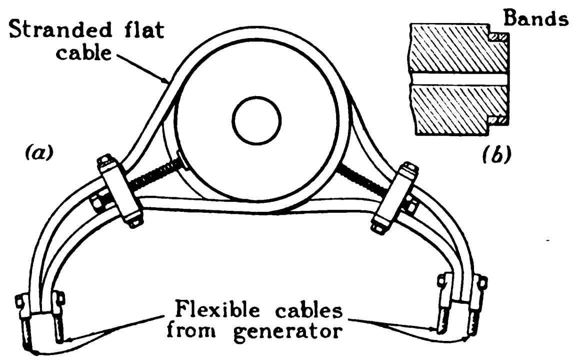

FIG. 7.

but concentration was first made upon magnetic and potential-drop methods. Magnetic methods were first tried because of their almost universal use in the testing of rails, ball races, etc., and, in addition, considerable information * was available on the correlation of the magnetic properties with the chemical composition, heat treatment and mechanical strength of steels.

This method proved to be too complicated when attempts were made to test after slotting had been carried out, but the results were much more hopeful with a smooth forging, when using magnetizing coils and search coils for measuring the flux distortion. The noise in the shop was found to be too great to allow the use of an interrupter and headphones in series with the search coil, and for that reason a ballistic galvanometer was used.

Before proceeding further with investigations on this method of detecting flaws, work was commenced on the potential-drop method, with such success that the magnetic method was abandoned in favour of this method, which has now been used for some years as a

* *Journal I.E.E.*, 1923, vol. 61, p. 949.

* "Correlation of the Magnetic and Mechanical Properties of Steel," Scientific Papers of the Bureau of Standards, 1916, No. 292; C. W. BURROWS and F. P. FAHY: "Magnetic Analysis as a Criterion of the Quality of Steel and Steel Products," also P. H. DUDLEY: "Magnetic Surveys of New and Failed Rails," and R. L. SANFORD and M. F. FISCHER: "Application of Magnetic Analysis to the Testing of Ball Bearing Races," *Technical Papers of the American Society for Testing Materials*, 1919, vol. 19, pt. 2; also papers by W. B. KOUWENHOVEN, C. NUSBAUM, N. J. GEBERT and S. R. WILLIAMS.

routine test. Potential-drop methods have been used for many years for the testing of all kinds of soldered, brazed and welded joints and have been compared from time to time * with magnetic methods. In the case of comparatively small ferrous products of uniform section, such as ball races and rails, the magnetic method has been preferred, and Spooner and Kinnard found it to give more consistent results.

The potential-drop method is more sensitive since

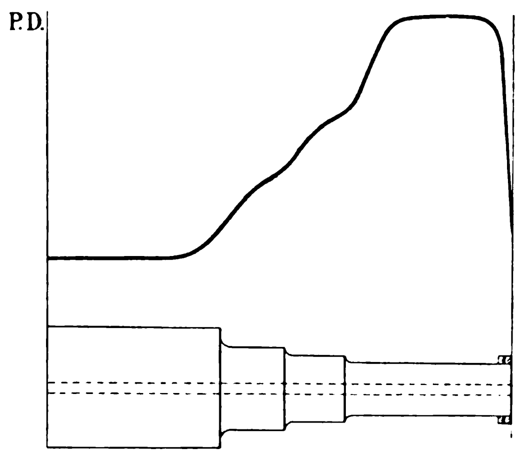

FIG. 8.—Electro bore test.

the ratio of electrical resistance of air to that of steel is far greater than the ratio of their magnetic reluctances. As its name implies, the test consists of passing a current and measuring the potential drop. Although this sounds quite simple and straightforward, in reality it gave considerable trouble when applied to forgings up to 45 tons in weight and 52 inches in diameter. The necessary direct current is obtained from a plating dynamo, and one of the minor difficulties was that of

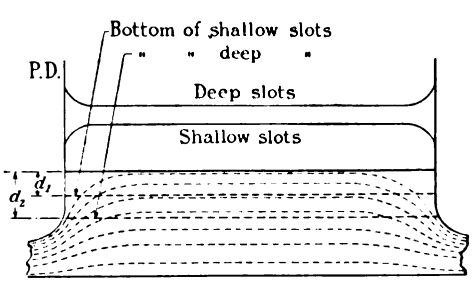

FIG. 9.—Slot test.

leading in the current to the rotor satisfactorily. Unless the current is led into the shaft uniformly, no reliance can be placed on tests made within 2 ft. of the leading-in bands. A satisfactory method is shown in Fig. 7 (*a*) which is self-explanatory. A better method, still using these bands, is to step the end of the shaft as shown in Fig. 7 (*b*).

It is not possible in this paper to give details of the apparatus used, but only to mention that the chief difficulties experienced were :—

(1) Alteration of spacing of contacts.
(2) Effect of stray fields.
(3) Thermo-couple effects.
(4) Contact-resistance effects.
(5) Fluctuation of current.
(6) Vibration of galvanometer.

Also, the design of the contacts had to be different for tests in the slots, on the shaft, and in the bore, in addition to variation in size of each of these for different sizes of rotors.

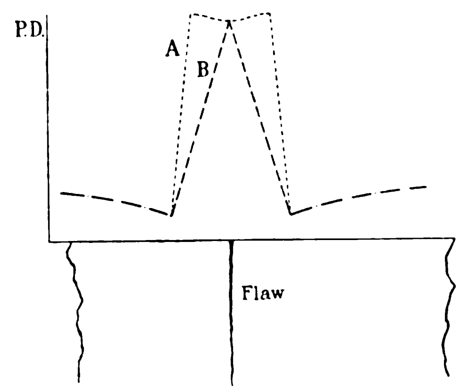

FIG. 10.—Characteristic curve obtained with flaw extending to surface of forging. *Note.*—Movement per reading in curve A one-fifth of that in curve B.

Fig. 8 shows the results of the "electro bore" tests using contacts 2 in. apart, and gives a good indication of the variation in potential drop obtained. This test would of course be carried out along a number of equally spaced axial lines, giving a number of identical curves if the shaft is satisfactory.

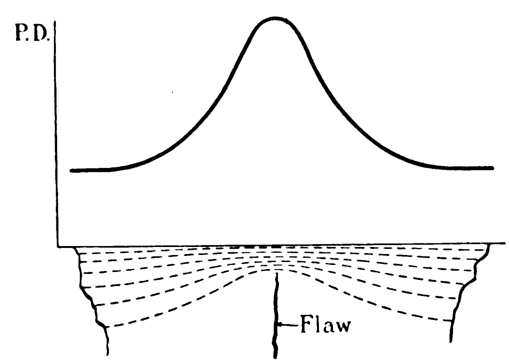

FIG. 11.—Characteristic P.D. curve obtained with crack below surface of forging.

Fig. 9 shows the type of curve obtained from readings taken along the bottom of the slots. It will be seen that the E.M.F. curves for the shallow slots fall at the ends, whereas for the deep slots they rise. The reason for this will be obvious when the current distribution as indicated by the stream lines is considered.

Figs. 10 and 11 show the essential difference obtained in the potential-drop curve, depending upon whether

* T. SPOONER and I. F. KINNARD: "Electrical and Magnetic Weld Testing as applied to Butt-welded Steel Plates," *Technical Papers of the American Society for Testing Materials*, 1922, vol. 22, pt. 2.

the flaw is buried or extends to the surface, whilst Fig. 12 shows the variation in potential with change in section, which, although perhaps at first is unexpected, is easily explained when the flow lines are considered and therefore needs no further comment, except that these results were taken with contacts spaced 1 in. apart, and that varying the contact spacing varied the form of the potential-drop curve very greatly.

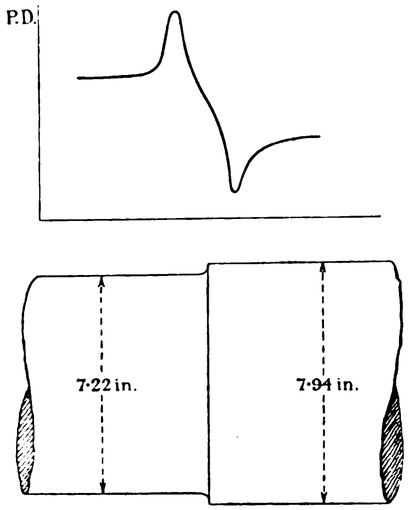

FIG. 12.—Variation of P.D. with change of section.

Fig. 13 shows the results obtained along the slots and on the rotor surface of a faulty rotor 22 inches in diameter, which had two large flaws spaced centrally so that they did not reach the surface. The shape of these cracks was similar to that of a double concave lens, the larger one being 16 inches and the other one 9 inches in diameter, as was shown on breaking up the forging.

When interpreting the results of the variation in the

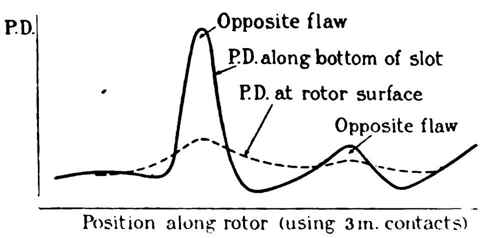

FIG. 13.—Curve obtained on faulty rotor.

potential-drop curves, it must be remembered that high or low deflections may be obtained even in a solid forging, due to the resistance varying with the chemical composition and heat treatment.

A broad view may be taken by saying that it is immaterial whether the forging contains a flaw or is not uniform in composition, as the boundary lines may form a plane of weakness. Whether this is so or not, there is the difficulty of getting the steel maker to agree with this. If the steel maker is notified that a variation is being found in a particular forging and that it will be rejected, he will undoubtedly agree to the cutting up of the forging for examination, and to bearing the loss if a dangerous flaw is found, "dangerous" because no forging is ever guaranteed to be free from small blow-holes. The question then arises as to what is a dangerous flaw, and that would have to be defined, as far as possible, before the forging was examined. It is not possible here to discuss this point, but it is mentioned as showing one of the difficulties which may arise, and it must be remembered that a forging, particularly of nickel steel, is an expensive component.

In the author's opinion, any variation in chemical composition occurring at the surface where the potential is being measured can be detected by making use of the thermo-couple effect. The thermo-couple E.M.F. varies with the chemical composition, so that if the points are moved along the rotor with no current passing it may be assumed if the deflection varies that the chemical composition is not uniform,* since only very small temperature gradients can normally exist in such a mass. It is also well to remember the work of Benedicks † who attempted to find a general formula for results of observations by other workers and himself for the variation of electrical resistance with chemical composition.

He established the following law of equiatomic solutions :—

$$O = 7\cdot6 + 26\cdot8\Sigma C$$

where O = specific resistance in microhms per cm^3,
$7\cdot6$ = resistivity of pure iron, and
ΣC = sum of the values of dissolved (in solid solution) elements in terms of carbon obtained by dividing the percentage found by analysis, by the atomic weight of the element multiplied by 12, the atomic weight of carbon,

or

$$\Sigma C = C + \frac{12\cdot0}{28\cdot4}Si + \frac{12\cdot0}{55}Mn + \frac{12\cdot0}{32}S + \frac{12\cdot0}{58\cdot7}Ni, \text{ etc.}$$

In general this formula gives fairly satisfactory results for dilute solutions where ΣC is not greater that 2–3 per cent and in some cases for more concentrated solutions of the ternary steel, as shown by Portevin, whilst in other cases it does not hold good.

In general it can be said that the resistance increases

(1) With the addition of elements,
(2) With temperature,
(3) With the amount of cold work,
(4) With hardening due to heat treatment.

In the case of rotor forgings we are chiefly concerned with plain carbon steels with not more than 0·5 per cent carbon, and 3·5 per cent nickel steels with 0·3 per cent carbon.

Benedicks gives the following figures for the variation

* L. DUPUY and M. PORTEVIN: "The Thermoelectric Properties of Special Steels," *Journal of the Iron and Steel Institute*, 1915, vol. 91, p. 306.

† "Recherches physiques et physico-chimiques sur l'acier au carbone" (Upsala, 1904).

of resistance with carbon, the percentage of the other elements being kept constant:—

Percentage of carbon	Microhms per cm³	
	Annealed	Hardened
0·08	10·51	10·9
0·16	12·59	13·6
0·23	13·74	15·4
0·33	14·67	17·2
0·38	15·11	18·3
0·48	24·03	28·99
0·55	27·54	34·36

It is also necessary to point out that a flaw running parallel with the current-flow lines gives practically no variation in P.D. and that the maximum distortion of current is obtained when the flaw is normal to the current flow. Any sign of variation of potential-drop not accounted for by a change in section is further investigated by leading in and out the current in the vicinity of the suspected flaw, thereby considerably increasing the current density and varying the path of the current flow according to the points chosen for leading the current in and out.

4. Mechanical Design.

(*a*) *Rotor*.—The improvement in the tensile strength of the rotor forging forms one of the most difficult problems of the turbo-alternator, because the designer is largely in the hands of the forge-master, and unless there is more co-operation than at present generally exists no great advances are likely to be made.

The routine testing of rotor forgings has for a long time consisted of taking tensile test and bend pieces as follows :—

(1) Longitudinal from one end of the shaft.
(2) Radial from one face of the rotor body.
(3) Transverse from the opposite face of the rotor body.

As previously mentioned, considerable segregation of the metalloids often takes place in large ingots, the top showing the higher percentage. With a given heat treatment the mechanical results are fairly sensitive to the carbon content and for this reason longitudinal test-pieces should be taken from both ends of the shaft, and the end of the ingot giving the more suitable carbon content should be chosen by the forge-master as the driving end of the rotor.

The shaft portions, owing to their comparatively small section, do not present any very great difficulty, but the rotor body is a different proposition. Rapid heating and cooling operations are not permissible owing to the dangerous stresses set up, and the difficulty of the mass annealing effect has to be confronted. Boring the rotor to the maximum diameter permissible by the shaft design immediately gives the steel maker greater freedom in heat treatment, with the result that the rotor as a whole is greatly improved.

Theoretically it can be proved that drilling a hole in a rotating disc doubles the stresses at the periphery of the bore, but in practice with ductile materials they are not so high and in rotor forgings give no trouble.

The limiting stresses in a rotor are at the bottom of the tooth, and it is necessary to know the strength of the steel in this vicinity, not only at the ends where the routine test-pieces are normally taken but along the whole of the tooth. The best that can be done is to trepan a test-piece from the centre (axially) of the rotor at a point through which a slot will finally be milled. As it is not advisable to go below the bottom of the slot, it is even then not possible to obtain the strength at the tooth root. The question therefore arises as to what is the ratio of the actual strength at the tooth root to that obtained by the normal routine tests from the rotor face. The author is of the opinion that the routine tests, without this knowledge, are of comparatively little use, particularly from the point of view of the designer, and that a trepanned test-piece taken as mentioned above is the only method of obtaining useful information. It is in this respect, that is, finding the ratio in strength given by a trepanned test-piece to that actually existing at the tooth root, that a great deal of work needs to be done, requiring the co-operation of the forge-master and the designer. At present, routine test-pieces are taken from the sections of the rotor into which most work is applied during the forging process, and the forging is heat-treated to give the best surface or test-piece results. The final solution may require the boring of the shaft to the maximum possible diameter, and heat treatment so as considerably to improve the strength at the tooth root, resulting probably in a considerable reduction in the quality (combined tensile strength and ductility) of the surface material now tested.

Every opportunity that occurs of investigating the variation of strength with depth should be taken. This is often possible where a large ingot is forged down in one piece and finally cut in half to produce two separate forgings. The investigation would have to cover the case of bored and unbored forgings, oil- and air-hardened, and of plain carbon and alloy steels. For instance, tests made in the case of air-hardened and normalized 0·4 per cent carbon steel forgings of about 30 in. diameter (not bored) show the following conditions to exist :—

	Routine test	Strength of tooth root
Yield point, tons/sq. in. ..	21·0	About 14·0
Maximum stress, tons/sq. in.	40·5	About 34·0
Elongation, per cent ..	26·0	About 12·0
Contraction, per cent ..	45·0	About 13·0

For this class of steel the limit of proportionality is about 75 per cent of the yield point.

It will therefore be seen that the yield point is only 15 tons/sq. in. at the tooth root, as against 21 tons/sq. in. for the routine test, giving a ratio of 15/21·0 or only 0·71. In addition to this the ductility is poor, as indi-

cated by the low percentage elongation and contraction, due to the coarse-grained structure produced by the effect of mass annealing. Oil-hardening carried out under the correct conditions will considerably increase the above ratio of 0·71, but treatment which will raise

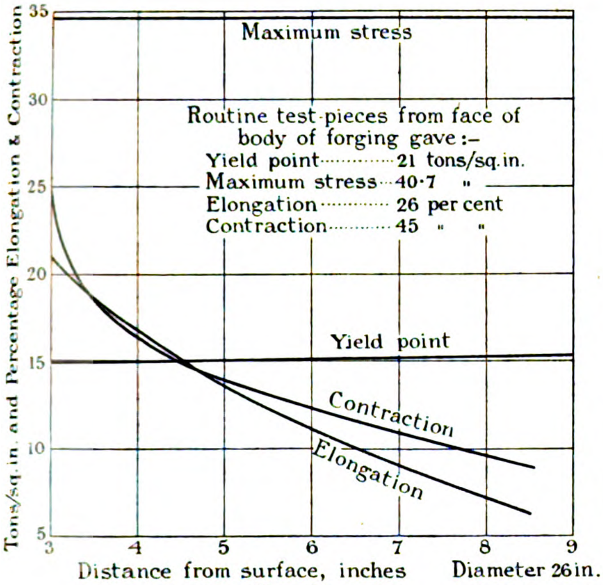

FIG. 14.

the yield point of a 0·4 per cent carbon steel to 25 tons/sq. in. should be avoided, as a 3·5 per cent nickel steel will give this strength in its "natural state."

The reduction of yield point and maximum stress with increased radial depth is comparatively small, as shown

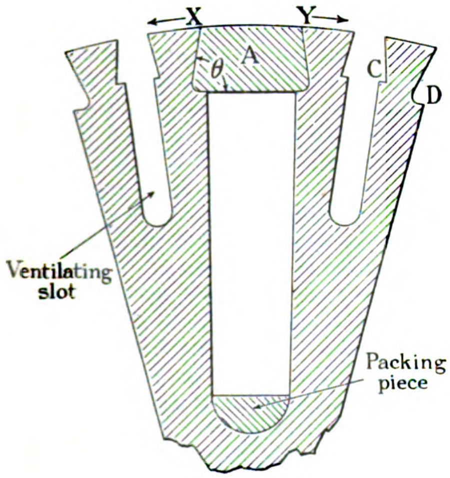

FIG. 15.

in Fig. 14, whereas the elongation and contraction show a continual reduction. A trepanned test-piece will therefore give a very good indication of the yield point and maximum stress at the tooth root, although the figures for the elongation and contraction so obtained will be considerably higher. In the author's opinion, therefore, the results obtained from a trepanned test-piece are infinitely more valuable than those given by the normal test-pieces and should be obtained in spite of the greater difficulty of trepanning.

For the following reasons and the considerations given above, the author recommends the design in which separate ventilating slots are placed between the main slots, as shown in Fig. 15, in preference to that illustrated in Fig. 16, where the ventilating slot is below the main slots. First, it gives the minimum slot depth and if the stress across CD is designed so that it does not exceed, or only just exceeds, that at the tooth root, the factor of safety will be greater than that obtainable with the design illustrated in Fig. 16, assuming equal copper loading in each case. Secondly, the deep, narrow slot is more efficient from the point of view of ventilation than the comparatively wide, shallow slot necessary under the main slots, whilst the circumferential slots need not be so deep. The largest possible diameter of rotor is used as in practice the output is found to vary

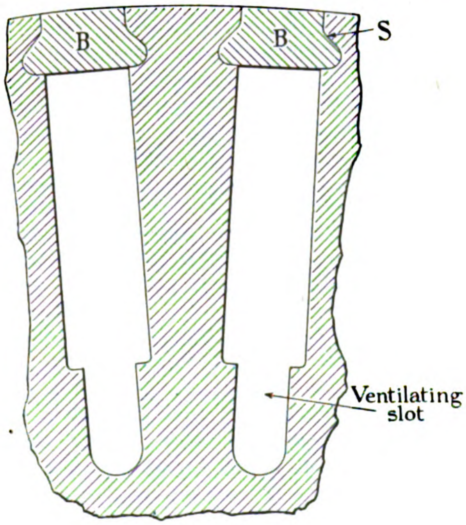

FIG. 16.

approximately as the cube of the peripheral velocity or diameter. In this respect it may be preferable in some designs to use aluminium in place of copper for the rotor winding.

All changes in section should be made as gradual as possible, particularly along the shaft, by allowing liberal and well-proportioned fillets.

The greatest stresses occurring in the shaft section are the alternating stresses at the neck of the journals, and the design of the shaft is governed by consideration of the value of this maximum stress, the critical speed (which must be kept well away from the normal speed, but not necessarily above it), and the bearing velocity.

(*b*) *Support rings*.—Almost without exception, a solid ring of steel of high tensile strength, or of high-tensile bronze in the case of single-phase alternators, is used for supporting the end windings. Stresses in such rings may be as high as 15 tons/sq. in. at 15 per cent overspeed, the self-stress being about 50 per cent of the total. This high self-stress suggests the possibility of using such light metals as duralumin, but,

apart from the difficulty of obtaining support rings in this metal, it will be found that a considerably higher factor of safety is obtained by means of a nickel-chrome steel, although duralumin would have the advantage of being non-magnetic.

The maximum circumferential strength is obtained by rolling in a similar manner to a railway tyre, and a steel having the following analysis :—

	per cent
Carbon	0·3
Silicon	0·15
Manganese	0·65
Sulphur	less than 0·05
Phosphorus	less than 0·05
Nickel	3·5
Chromium	0·6

when suitably hardened and tempered will give a tensile strength of :—

Yield point, tons/sq. in. ..	58
Maximum stress, tons/sq. in. ..	65
Elongation, per cent	20
Contraction, per cent	50
Brinell hardness (3 000 kg; 10 mm ball)	300
Impact test (Izod)	Not less than 35 ft.-lb.

Cold bend test. Test-piece $\frac{3}{8}$ in. × $\frac{3}{4}$ in. with rounded edges of $\frac{1}{16}$ in. radius must bend 180° with $\frac{1}{2}$ in. radius (over thinner section) without signs of fracture.

Considerably higher results may be obtained by the addition of molybdenum and an increase in the chromium content.

The chief disadvantage of such a steel is that it is very sensitive to heat treatment. Ni-Cr steel, when properly heat-treated, usually combines the toughness due to nickel and the hardness due to chromium, and at the same time appears to be free from the disadvantages of either, but in general it suffers from temper brittleness induced at a temperature of about 500° C. to 550° C. and it is chiefly for this reason that a minimum impact strength should be specified.

Support rings have been known to have serious ingot corner segregations * forming radial planes of weakness which have been detected by means of sulphur prints.

Although the support rings may not finally define the limit of peripheral speed to which the rotor may be run, yet they may become the controlling factor with regard to the minimum size of air-gap used, as the end bells have to be passed through the stator bore.

For single-phase machines a high-tensile manganese bronze having the following tensile strength when in the form of a support ring may be used.

Yield point, tons/sq. in.	35
Maximum stress, tons/sq. in.	50
Elongation, per cent	12
Contraction, per cent	20
Brinell hardness (500 kg; 10 mm ball) ..	190

* T. H. Turner: "Experiences in the use of Nickel-Chrome Steels." Paper read before the Staffordshire Iron and Steel Institute, 1922.

If it is possible to allow a little lower yield point and maximum stress, then the elongation and contraction may be considerably increased.

It is difficult to see why such alloys are known as bronzes, because the tin content is usually below 1 per cent, whilst the zinc is in the region of 35 per cent, with about 2 per cent each of iron and manganese, the remainder being copper, although aluminium is often added. The disadvantage of such bronzes is that under no circumstances must hot solder or mercury be allowed to come into contact with them, owing to the property of solder and mercury of penetrating the intercrystalline interstices of the bronze, producing rapid weakening which may result in failure.

Difficulty was originally experienced with steel support rings owing to the high induced voltage which occurs on breaking the field, or during a single-phase or three-phase short-circuit, causing large currents to flow along the rotor keys and teeth and back via the support ring. The author has examined some early machines returned for repair where there was definite indication of local overheating and arcing having taken place from this cause. Such points of the support rings were glass-hard and could not be filed, and had they been incorrectly spigoted might have failed.

Two methods of overcoming this suggest themselves. One is to prevent such currents flowing, and the other to provide a low-resistance circuit through which the current can pass without arcing. The latter method has been extensively used by a number of firms who provide bonding strips of copper running underneath the main wedges and sandwiched between the windings and support rings. Such an arrangement really constitutes a medium-resistance damping winding and has been found to give perfectly satisfactory results.

(c) *Wedges.*—One of the two types of wedge shown in Figs. 15 and 16 is generally used and both have given good results. The T-shaped wedge is easier to fit because a slight error in the slope S does not seriously affect the fit and, in addition, the area of the surface of the slope S is small compared with that of the plain wedge. When the angle θ of the latter is in the neighbourhood of 75° to 80° the fitting has to be done much more carefully, and the stresses in the direction X and Y are about six times the radial stresses. With a given width for the slot and base of wedge, the plain wedge is the stronger, but on the score of ease of fitting the author favours the T-shaped wedge, particularly where a wedge extending the whole length of the rotor has to be fitted, instead of sections about 1 ft. long.

In three-phase machines magnetic wedges are necessary in the region of the pole centre, and non-magnetic wedges in the neutral, in order to reduce the cross leakage flux as far as possible. In the case of the single-phase alternator, wedges of high conductivity (in addition to being non-magnetic) are required in order that an efficient damping winding may be formed. The material used, both magnetic and non-magnetic, must have considerable strength and not bind when being driven into position.

The tensile strength and conductivity of some suitable metals for wedges are given below :—

	Steel	Hard-drawn phosphor bronze	Extruded bronze
Yield point, tons/sq. in.	24·0	33·0	30·0
Maximum stress, tons/sq. in.	42·0	34·0	44·0
Elongation, per cent ..	26·0	13·0	25·0
Contraction, per cent ..	45·0	48·0	35·0
Brinell hardness (10 mm ball)	200·0 (3 000 kg)	155·0 (500 kg)	150·0 (500 kg)
Resistivity (microhms per cm^3 at 15° C.) ..	18·0	10·5	12·0

When testing wedges in a jig made in the form of the wedge slot, the load must be applied through a copy of the slot winding and insulation. If a solid steel tool the same width as the copper is used to apply the load, the wedge will fail in shear, whereas under normal conditions the wedge fails at a lower figure by bending as a beam. It is also necessary to remember that whereas in such a test all the load is applied to the wide face, yet under normal operation the load distribution becomes modified, owing to the wedge self-stress.

Wedge stresses at 15 per cent overspeed may be as high as 5·5 tons per inch length, but even then a factor of safety of 2½–3 is obtainable, which is ample when the uniformity of extruded and hard-drawn wedges is considered.

5. Ventilation and Liquid Cooling.

(*a*) *Liquid and air cooling.*—On comparing the heat-carrying capacities of air, water and oil, as given below one is perhaps at first rather surprised that liquid cooling has not been universally adopted, but a careful examination shows that a number of other important factors enter into the problem.

(*a*) Ratio of weight per unit volume :—

$$\frac{\text{1 cub. ft. of water}}{\text{1 cub. ft. of air (760 mm barometer, 38° C.)}} = \frac{62\cdot4}{0\cdot0711} = \frac{878}{1}$$

(*b*) Ratio of specific heats : $\frac{\text{Water}}{\text{Air}} = \frac{1\cdot0}{0\cdot242} = \frac{4\cdot13}{1}$

(*c*) Ratio of normal velocities obtained :—

$$\frac{\text{Water}}{\text{Air}} = \frac{\text{500 ft./min.}}{\text{4 500 ft./min.}} = \frac{1}{9}$$

Therefore ratio of heat-carrying capacity of water to air under normal conditions is :—

$$\frac{\text{Water}}{\text{Air}} = \frac{878}{1} \times \frac{4\cdot13}{1} \times \frac{1}{9}$$
$$= 400 \text{ with equal temperature-rise of both mediums.}$$

For transformer oil having a specific heat of 0·47 at 30° C. and a specific gravity of 0·83, and a velocity of 500 ft. per min., the ratio of oil to air cooling is

$$\frac{400 \times 0\cdot83 \times 0\cdot47}{400} = \frac{156}{400} = \frac{1}{2\cdot5}$$

The above advantage would not be realized in practice because, whereas in air cooling the temperature-drop is from surface to air, with liquid cooling it is from surface to water tube and then from tube to liquid. However, the advantage is considerable, for in air-cooled machines the heat dissipation is of the order of 1½ watts/sq. in. with 25 deg. C. air temperature-rise, whereas a tube 1 inch in diameter with a velocity of 500 ft./min. and a temperature difference of 15 deg. C. dissipates about 80 watts/sq. in.

The standard air-cooled design shown in Fig. 15 if converted to water cooling would have an increased cooling capacity of the order of 40–50 times that of the air-cooled design. As there is a large temperature-drop across the insulation, this increase in efficiency could not be utilized owing to the inability of the remainder of the heat paths to transmit the heat to the duct.

In the author's opinion the extra complication of liquid cooling will not be justified until insulating materials with very much greater heat-carrying capacities than that of micanite are found. In addition there are the following disadvantages :—

(*a*) Extra complication, needing a high-pressure water circuit up to 1 000 lb./sq. in.
(*b*) Danger of water leakage causing failure of the insulation.
(*c*) Danger of clogging and corrosion of water pipes or sludging of oil.
(*d*) Loss of the heat-dissipating surface of the stator and rotor at the air-gap, which forms a large proportion of the total surface.
(*e*) The end winding would have to be in contact with large liquid-cooled metal clamps. Although this would be advantageous from the point of view of supporting the coils, it considerably increases the stray losses in the case of the stator and these are already very high. In addition, a greater thickness of insulation would be required.

Difficulty in ventilation is experienced with the rotor in high-speed machines and with the stator in low-speed machines. In the case of the stator, water cooling would have the advantage of allowing a better mechanical construction, owing to the elimination of the comparatively flimsy core spacers.

If, as in this country, very much larger units than 25 000 kVA at 3 000 r.p.m. and 50 000 kVA at 1 800 r.p.m. are not required, then water cooling should not be adopted until air cooling is definitely proved to be inferior, when considered from the point of view of reliability, efficiency, ease of operation and first cost. This will need considerable investigation on the lines indicated below.

In practically all large machines a combination of axial and radial ventilation is adopted and, although the design details vary considerably, the essential prin-

ciple is that of splitting up the air paths into a large number of comparatively short parallel paths, resulting in large volumes of air at comparatively low pressures and a uniform distribution with the elimination of hot spots. The ventilating spaces occupy about 20 per cent of the stator volume, and the stator core laminations are divided up into axial packets of about 2 in. separated by ducts of about $\frac{3}{8}$ in. to $\frac{1}{2}$ in.

Volume of air required.—The specific heat of air is 0·242, therefore 0·242 B.Th.U. will raise 1 lb. of air 1 deg. F., and $0 \cdot 242 \times \frac{9}{5}$ B.Th.U. will raise 1 lb. of air 1 deg. C.

Volumes of air are usually dealt with in terms of cubic feet, and under the normal conditions of 760 mm barometer and 38° C., the weight per cubic foot is 0·0711 lb. Therefore to raise 1 cub. ft. of air 1 deg. C. $0 \cdot 242 \times \frac{9}{5} \times 0 \cdot 0711 = 0 \cdot 031$ B.Th.U. is required.

$$\text{Since} \qquad 1 \text{ B.Th.U.} = 778 \text{ ft.-lb.}$$

$$\text{and} \qquad 1 \text{ watt} = \frac{33\,000}{778 \times 746} = 0 \cdot 0568 \text{ B.Th.U.}$$

$$1 \text{ watt will raise } \frac{0 \cdot 0568}{0 \cdot 031} = 1 \cdot 83 \text{ cub. ft. 1 deg. C.}$$

$$\text{or} \qquad (\text{cub. ft. per min.}) = 1 \cdot 83 \times \frac{\text{watts loss}}{t \text{ deg. C. rise}}$$

The loss in a large alternator is about 4 per cent of the output, or kW × 0·04

$$\therefore \ (\text{cubic ft. per min.}) = 1 \cdot 83 \times \tfrac{40}{20}$$
$$= 3 \cdot 66 \text{ cub. ft. per kW output with 20 deg. C. rise.}$$

This air cannot always be used to the best advantage, and a figure of 4·0 cub. ft. per kW output is generally taken for a 20 deg. C. temperature-rise, i.e. a 15 000 kW alternator requires about 60 000 cub. ft. of air per minute.

In dealing with ventilation problems a full knowledge is required of the distribution and magnitude of the losses, and the paths by which the heat reaches the cooling medium.*

The air-flow problem, although analogous to that of the electrical circuit, is considerably more complicated, in that the true laminar flow obtained in pipes at low velocities (giving a parabolic variation of velocity across the tube) does not exist. The flow throughout the system is practically turbulent, and in the case of air leaving the rotor radial ducts and meeting the stator bore it is violently turbulent. Turbulence, in addition to complicating the calculation, gives a very much reduced flow under a given pressure, but has the advantage that the "scrubbing" effect on the sides of the duct greatly increases the heat conductivity. This is due to the fact that in laminar flow there exists a thin cylinder of stationary air, which has the low heat conductivity of about 0·0002 watt per cm³ per deg. C., compared with 0·003 for built-up micanite.

By applying temperature/density corrections and assuming air to be an incompressible fluid, a number of the constants used in hydraulics can be employed with fairly satisfactory results. The assumption that air is incompressible is justified in ventilation problems because of the relatively small pressures dealt with. The normal atmospheric pressure is about 407 in. of water, whilst the highest pressure used in an alternator is about 12 in., i.e. 3 per cent of normal.

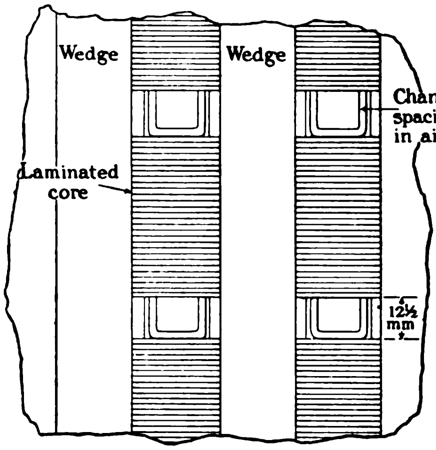

FIG. 17 (*a*).—Plan of stator periphery.

All air problems are somewhat laborious, owing to the rapid changes in duct section and direction of flow which take place in the alternator, and the more simple and definite method is to carry out tests on wooden models. For example, Figs. 17 (*a*) and 17 (*b*) show a plan of the stator bore and a section through a duct, showing how the wedge and **U** spacing piece reduce

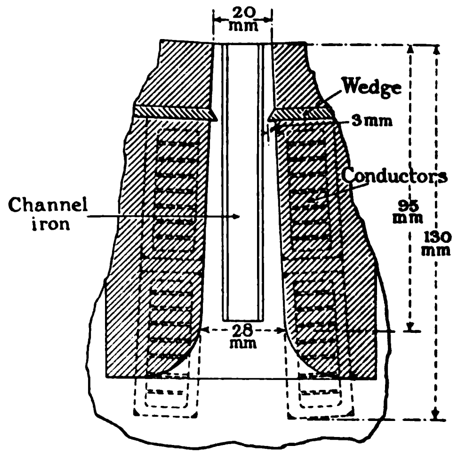

FIG. 17 (*b*).—Section through duct.

the effective area of the duct. The shaded section in Fig. 17 (*b*) (to scale) denotes the dimensions of a wooden model made up by the author to determine how the volume and pressure of the air are affected by the wedges and spacers.

The design of the air circuit of an alternator may be such that the air has to travel in one direction through some of the ducts and in the opposite direction in the

* C. I. J. FECHHEIMER: "Longitudinal and Transverse Heat Flow in Slot-wound Armature Coils," *Transactions of the American Institute of Electrical Engineers*, 1921, vol. 40, pp. 332 and 421.

others. Figures were therefore taken in both directions with the following combinations :—

(1) Plain duct without wedge projection and channel spacer.
(2) With wedge only.
(3) With channel spacer only.
(4) With channel and spacer.

Fig. 18 gives the results in the form of curves, the full lines indicating that the air was flowing from the large to the small end of the duct and the dotted lines vice versa. It will be seen that the volume of air with a given pressure is highest for condition 1, and decreases in the order of 2, 3 and 4. These results are exceptionally interesting and instructive, as will be seen by taking

It will be seen that cutting away the small piece of wedge which protrudes 3 mm into the slot allows 35·5 per cent more air to pass with a given pressure, and that with a given volume the pressure is very much reduced. What is more important is that the protruding wedge does not allow the air to "scrub" the sides of the coil, thereby eliminating the most important characteristic of turbulent flow.

It is therefore recommended that **I**-shaped spacing pieces be used and that the wedges be notched before being driven into position. The **U** spacer also has the disadvantage that the bearing area at the open side is comparatively small, resulting in high local mechanical stresses.

The problems of the correct shape and size of duct,

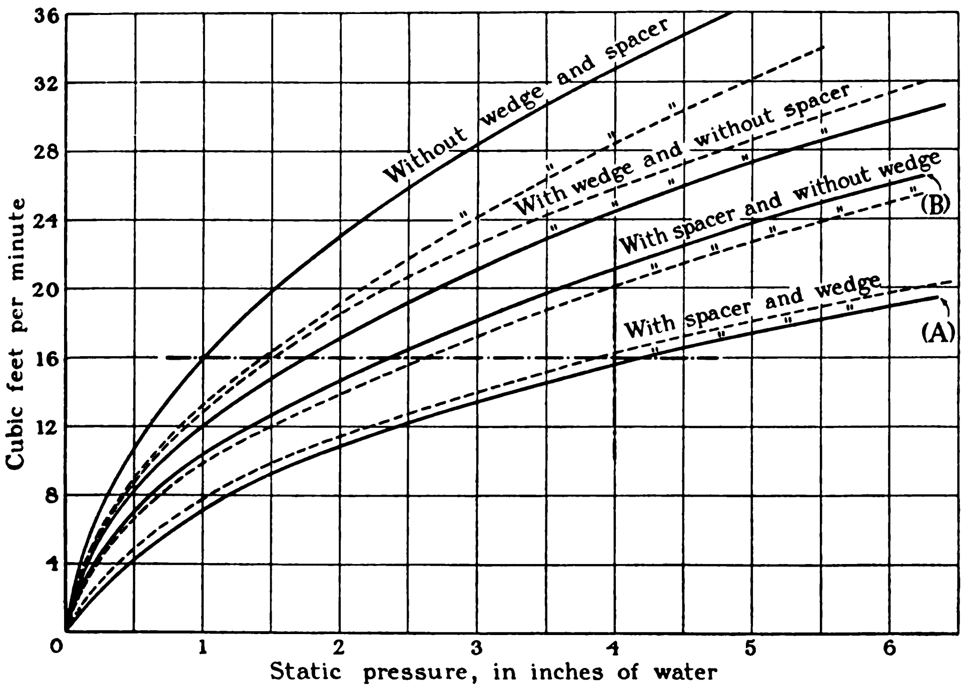

Fig. 18.

only one comparison. Suppose that the small section of wedge projecting into the air duct be removed, what alteration would take place in the volume of air passing the duct when compared with the normal condition in which both the wedge and spacer are used ?

At a pressure of 4 in. of water, comparing the two conditions with air flowing from large to small end, we have :—

With wedge and spacer (Curve A) .. .. .. 15·5 cub. ft. per min.
Without wedge (Curve B) 21·0 cub. ft. per min.
i.e. an increase of 35·5 per cent

or, suppose 16 cub. ft. per min. are required :—

Without wedge, pressure (Curve B) = 2·37 in. of water
With wedge projection, pressure = 4·25 in. of water
or an 80 per cent increase.

The air temperature for the above tests was 12·5°C.

the position for such ducts, and the relative proportion of axial and radial ducts are by no means yet solved. For instance, the axial system of ventilation, with its disadvantages, has the great advantage that the heat flow is in the plane of the laminations, whereas in the radial system the flow is across the laminations. It is found that the rate of heat flow across the laminations is only about 1/40th of that in the plane of the laminations, and only about 4–5 times greater than that across the insulation.

(*b*) *Wet and dry air filters and closed air systems.*—In the author's opinion, the only suitable method of supplying clean, cool air to the alternator is by means of a closed air system in which the air is cooled by passing between "gilled" water tubes, with a fan either separately driven or carried on the rotor. The closed system is more expensive than the wet or dry air systems, although the inlet and outlet ducts are more

simple. A closed system with a volume of 0·1 cub. ft. per kW has been found to give satisfactory results on a 15 000 kW alternator.

The closed air system has the disadvantage that in some cases there may be difficulty in providing the necessary cooling water (temperature-rise of 10 deg. C. satisfactory) which is preferably taken from the condensate. Apart from this its advantages are :—

(1) The elimination of all foreign matter likely to interfere with the ventilation.

(2) Its great advantage from the point of view of fire, owing to the small volume of 0·1 cub. ft. per kW and the fact that air with a comparatively small percentage of CO_2 will not support combustion. Arrangement for the use of artificial fire-extinguishers is simplified, although these appear unnecessary and should not normally be used owing to the adverse effect on the insulation.

(c) *High-speed and low-speed separately driven fans.*—In spite of the fact that on the score of reliability and ease of operation the high-speed fan carried on the shaft is superior to a separately driven fan, its disadvantage and the advantages of the separately driven fan make it difficult to decide which of the two is the better system.

The operating engineer will undoubtedly favour the high-speed fan carried on the rotor, whereas the designer who has to see that the machine is up to specification must favour the separately driven fan. The relative merits and demerits of each are as follows :—

(1) In the high-speed fan practically all the velocity "head" is lost owing to the difficulty of providing a suitable vortex chamber, and the temperature-rise of the air due to friction is greater than that given by a separately driven fan.

(2) The increase of temperature due to the air passing through the fan is not serious with the separately driven fan, particularly as the cooler is placed on the discharge side of the fan.

(3) The high-speed fan requires about 13 kW per 1 000 kW output, or a little over 1 per cent, and the separately driven fan less than 6·5 kW per 1 000 kW output.

(4) The high-speed fan may actually limit the output possible with high-speed machines because of the difficulty with critical speed owing to the increased length of shaft necessary to allow of a suitable air chamber being formed in the end bell.

From the above consideration the author is of the opinion that a low-speed fan driven by a 750-r.p.m. d.c. shunt-wound motor or a squirrel-cage induction motor is the more attractive proposition of the two, even bearing in mind the disadvantages in respect to ease of operation.

6. Insulation and Temperature Distribution.

From the design point of view, the higher the temperature-rise permissible the better, provided that increase in temperature does not reduce the reliability and life of the insulation. There is little doubt that unnecessarily low temperature-rises force the designer to use an elaborate system of ventilation, resulting in a less reliable machine.

The temperature-rise specified must always be considered in relation to the method used in its determination, that is, thermometer, change in resistance, or thermo-couples. Since the air temperature is variable it is always better to deal with actual temperatures rather than temperature-rises, particularly as it is the maximum temperature reached which has to be definitely limited. In addition, this maximum temperature must be that of the "hot spot."

Measurement of temperatures by thermo-couples.—Owing to the large temperature gradients existing in the turbo-alternator it is obvious that the thermo-couple method is far superior to the thermometer and change-in-resistance methods. The thermo-couple has of course to be placed outside the insulation, both because of safety and the increased difficulty of insulating the coils.

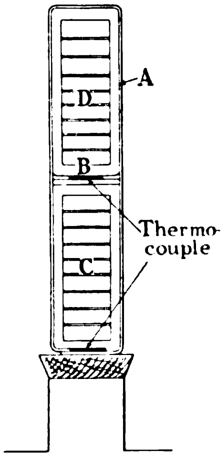

Fig. 19.

They are of course placed near the coils adjoining the star point, which is normally earthed, but there is the possibility that, due to line disturbances, the E.M.F. may rise to a dangerous value. The general use of thermo-couples for large turbo-alternators has considerably helped the designer, for although he had realized long before the operating engineer that very high temperatures next to the copper must exist, yet he was not able (because of the low specified temperature) to carry out tests on site which would raise the operating engineer's suspicions, even though the designer knew that such high temperatures were not dangerous.

Having fixed on a maximum permissible temperature, it is necessary to know the relation between the temperature of the insulation next to the copper and that attained by the thermo-couple. This may be estimated as follows :—

$$\text{Temperature-drop} = \frac{\text{Watts/sq. in. of coil} \times \text{thickness of insulation}}{\text{Thermal conductivity of insulation}}$$

Fig. 19 shows the stator design using two bars per

slot, and the constants applicable to such coils are as follows :—

Watts/sq. in. in top coil C = 0·8.
For the bottom coil D the figure may be as much as 20 per cent lower, owing to the lower eddy-current effects.
Thickness of insulation for 5 000–6 000 volts = 0·11 in.
Thermal conductivity of compact micanite = 0·003 watt per 1 in. cube per 1 deg. C.

∴ Temperature-drop through insulation

$$= \frac{0 \cdot 8 \times 0 \cdot 11}{0 \cdot 003} = 29 \text{ deg C. at point A}$$

At the point B there is little heat transferred between the coils, although there will be some flow from the packing piece to the sides of the slot. If the couple placed at B is fairly narrow, the slot comparatively wide, and the spacing insulation thin, the difference between the copper temperature and the temperature indicated by the thermo-couple, known as the "conventional allowance," should not be large for a 105° C. maximum-temperature, 5 000–6 000-volt alternator.

F. D. Newbury * gives the following figures :—

Volts	Thickness of insulation	Top coil temperature-rise	Insulation temperature-drop	Conventional allowance
	in.	deg. C.	deg. C.	deg. C.
6 600	0·15	65	30	6·6– 8·4
13 200	0·25	65	40	8·8–11·2

For machines operating at 13 200 volts and a maximum temperature of 150° C. the conventional allowance may be considerably higher, and investigation in this direction is necessary. It may, however, be assumed that, under less extreme conditions, the actual copper temperature will not be more than 10 deg. C. above that indicated by the thermo-couple. Care should be taken to fix the couple as close to the hot spot as possible, i.e. approximately mid-way between two radial air-ducts. Failure to do this may result in damaging the machine owing to overloading, due to the supposed temperature of the couple being considered to be only 10 deg. C. below that of the hot spot. The position of the hot-spot temperature will depend upon the design, but it will normally be found in the embedded portion of the stator winding either at the ends of the core or in the middle (in axial direction), and for this reason a number of couples should be fitted. In the case of the rotor, however, the end winding is considerably higher in temperature than the slot portion.

Recommended methods of insulating.—All modern turbo-alternators are insulated by means of micanite moulded on to the straight embedded section and applied in the form of tape to the end windings. One method consists of using stranded conductors in order to cut down the eddy currents, and using comparatively soft micanite in order to allow the copper a certain freedom of movement during expansion. Such micanite is kept soft by the addition of oils which it is claimed do not oxidize, owing to the exclusion of air. This is not the author's experience, and a conductor built up of copper strips spaced by micanite and surrounded by a hard moulded micanite tube with a high percentage of mica forms a better construction. By suitable transposition of the conductors from slot to slot, eddy currents can be reduced to a value comparable with that given by the stranded conductor, with the great advantage of added strength, which is very important both from the point of view of handling during winding and of the subsequent operation of the machine. Increasing the voltage also reduces the eddy currents, and in many cases a 13 000-volt generator is preferable to one of 6 600 volts.

Hard micanite is recommended because soft micanite may be soft at first but soon hardens, whilst in the case of hard moulded micanite the copper can be given freedom of movement (without damaging the insulation) by dipping it, before insulating, in a compound of the bitumen type having the following properties :—

Coke	40 per cent
Ash	0·2 per cent
Dropping point (Kraemer and Sarnow)	100° C.
Electric strength	600 volts per mil for 1 mm thickness at 90° C.

Such a compound is very stable chemically, as all bituminous compounds are in general, and does not harden with prolonged heating at the temperature likely to be reached in an alternator.

The slot micanite should contain a minimum of shellac and paper. These have to be used in order to apply the mica by means of automatic wrapping machines and to fill the air spaces. The proportion of mica by volume should not be less than 60 per cent, and with very special care it is possible to increase this to over 80 per cent, the proportion of mica by weight reaching 95 per cent, but at present this is not commercially possible.

A coil insulated with a 60 per cent micanite wrapper will give an electric strength of 550 volts per mil cold, and 450 volts at 100° C. Pressures much exceeding 90 volts per mil result in ionization if air pockets are present, and normally the thickness of the insulation is based on a stress of 50 volts per mil. Care has to be taken during the moulding of the micanite, owing to the possibility of the formation of acid distillates from shellac and other gums at certain temperatures.

The end winding should be insulated with micanite consisting of not less than 70 per cent mica by volume, and the following tape will give good results :—

Total thickness	7·5 mils
Mica thickness	5·3 mils
Silk + varnish + oils	2·2 mils

The least possible amount of varnish consistent with the filling up of the air spaces should be applied to each layer. The final layer is often of cotton tape, which is

* "Probable Values of Conventional Allowance for A.C. Generator Stator Windings," *Transactions of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 636.

varnished and is chiefly applied for mechanical reasons. The author is of the opinion that an asbestos tape, which can now be obtained of considerable strength, should be used and the varnish or liquid should be of the fireproof type, which is easily obtainable provided electric strength is not of importance. Meanwhile, it is necessary to wait for the chemist to discover an insulating material having the electric and heat-resisting properties of mica but with a very much greater heat conductivity.

The use of open slots allows the fitting of tight coils, with a minimum of trouble and damage to the coils, and although semi—and tunnel—slots may give slightly better wave-forms, yet the ripple with open slots may be kept down to 3 per cent.

The foregoing has dealt chiefly with the insulation of the stator, but the same principles apply to the insulation of the rotor. In the rotor, however, very high mechanical stresses exist and, although the voltage is normally not above 400, it may in some cases have high instantaneous values. For these reasons, in the slot portions only micanite is suitable, whilst on the end windings strong asbestos tape may be used for the outside of the coils, which are spaced and supported by materials of high heat-resisting properties, such as bakelite asbestos.

Maximum temperatures.—The maximum temperature of 160° C. has been suggested as satisfactory for micanite-insulated alternators, but the indefinite information available does not appear to justify a maximum safe temperature above 130° C. Results of many tests have been published, from which conclusions have been drawn that 200° C. is not too high, but a careful examination of the methods of test used reveals that the practical conditions have been far from imitated. One of the difficulties with high temperatures is the difference in expansion of the copper, the insulation, and the core iron respectively, which in many cases has resulted in the failure of the alternator due to the gradual disintegration of the insulation. Most of the tests take care of expansion but do not include the very important factor of vibration, and, in fact, the imitation of practical conditions is exceedingly difficult; and some tests show that a temperature of 160° C. must be approached with caution.

The benefit of a permissible increase in temperature can only be made full use of by re-proportioning the copper and iron volumes, as the following example will indicate. Assume a rotor designed for 100 volts and 100 amperes, and having under such conditions a temperature-rise of 100 deg. C.; and assume also that the temperature-rise increases in direct proportion to the losses (actually it increases at a greater rate). On this assumption we have that the increase in kW from 10 to 20 gives a temperature-rise of 200 deg. C., or twice the normal.

We have, say $R_{100} = 1\cdot 0$ ohm

then $R_{200} = 1\cdot 4$ ohm

$$I^2R = EI = 20\,000$$

$$1\cdot 4I^2 = 20\,000$$

Therefore $$I = \sqrt{\frac{20\,000}{1\cdot 4}} = 119\cdot 5 \text{ amperes.}$$

This indicates that an increased allowance in temperature-rise of about 100 per cent would result in an increase of only 19·5 per cent in the exciting current.

The author is aware of cases where information given by thermo-couples has been misused owing to the belief that, since the maximum temperature of the alternator is known, practically any treatment as regards overload can be given without danger; this is not so. The author would particularly refer to the case of the dry-out of large alternators in which the short-circuit current is increased above the normal in order to raise the temperature rapidly to, say, 105° C. as indicated by thermo-couples, whilst the full volume of air is allowed to pass through the machine. By this means the copper reaches a high temperature before the iron has heated up, in which case the worst possible conditions exist as regards expansion, resulting in possible fatal damage to the machine. The correct procedure for the dry-out of an alternator of, say, the closed-air type, is as follows:—Run the machine at any convenient speed and increase the short-circuit current so that the temperature is gradually raised in 16 hours to 85° C. with only a small volume of air passing over the windings. Run for 6 hours at this temperature, slowly increasing the volume of air to the maximum and the temperature to 100° C. as indicated by thermo-couple. During this test no water should be allowed to circulate in the cooler, and arrangements should be made for completely changing the air at the rate of once in every 4 hours. This is best carried out gradually by providing a leak in the duct. Apart from the elimination of the expansion trouble, the gradual increase in temperature allows the insulation to "settle down" slowly.

7. Balancing.

On high-speed alternators balancing has to be very carefully carried out, particularly as it is necessary in the case of large 3 000-r.p.m. machines to run through the first critical speed. The balancing of a turbo rotor is more difficult than that of a turbine disc, because of the centrifugal couples introduced by the heavy points not being in the same transverse and axial planes. With built-up rotors it is preferable to balance along the rotor body, but in the case of the solid forging it is found sufficient to balance at each end, because of the rigidity of the body.

It is the correct combination of weight and position which makes it so difficult to balance correctly. If the positions at both ends are found, then seven-eighths of the work of balancing is done. The most common methods used for dynamic balancing are:—

(1) Trial and error.
(2) Marking the "high point" at full speed.
(3) Measuring the reactions on the bearings and the phase of the force and applying a calculation.
(4) Mechanically balancing the centrifugal couple set up.

The trial-and-error method may take anything up to a week, whilst for (2) the rotor should be run in both directions owing to the mark indicating the high point

being out of phase with the out-of-balance point by an amount depending upon the speed of rotation.*

All three methods are indirect and indefinite and for that reason attempts have been made to alter the position of the balance weight when running at full speed. The author suggests the following method, which so far he has been able to try on only a small model. Essentially the scheme is a "position finder," but it will give a good indication of the out-of-balance weight.

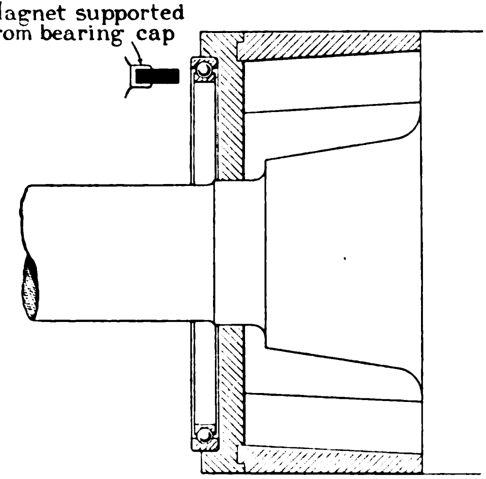

FIG. 20.

For simplicity it will be first assumed that we have a standard ball bearing and that the outer race fits into a concentric groove in the end plate of the rotor as shown in Fig. 20, the inner race being free to move. With the rotor running at full speed the whole race rotates in synchronism with the rotor. If now a magnet supported from the bearing cap, as shown in the figure, is excited it will cause the inner race to lag and so alter its position and the position of the balls. If an out-of-balance weight is fixed to the inner race its position will therefore alter. The out-of-balance weight may also be obtained by using duralumin for some of the steel balls (the specific gravity of this metal is 2·8 as against 7·8 for steel). The whole apparatus can be watched through a stroboscopic disc rotating with it, and the position of the weight can be observed in relation to markings in degrees on the outer race. On the small model the position of the inner race was found to be easy to control and, in addition, due to the centrifugal force no slipping occurred after a few hundred revolutions per minute, even when rapidly accelerating and decelerating.

The scheme put forward has, of course, difficulties, but owing to the very indirect methods now available it may be worth while developing. It will be seen that if an out-of-balance weight is placed on the inner race and balls of different weight are also used, we have two independent heavy points which move at different rates, with the result that it would also be possible to vary the amount of out-of-balance as well as its position. This is a complication and the best use of the apparatus would probably result by employing it as a "position finder."

In conclusion the author desires to express his thanks to Mr. Orsettich, Chief Engineer of the General Electric Co., and Mr. Bartlett of the Development Department, for permission to use some of the information contained in the paper. He also wishes to acknowledge the assistance which he received from Mr. Clutterbuck, Mr. Spruce and Mr. Cooper of the Development Department in making the slides and drawings.

* MILES WALKER: "The Diagnosing of Troubles in Electrical Machinery," p. 107.

DISCUSSION ON "MEASUREMENTS IN ELECTRICAL ENGINEERING BY MEANS OF CATHODE RAYS." *

Mr. N. Kipping (*communicated*): Although, as the authors indicate on page 1088 (vol. 63), the Western Electric cathode-ray oscillograph is not specially arranged for photographic work with a camera, yet I believe that the exposure figures quoted are somewhat in excess of those necessary with the "mixed" fluorescent screen of calcium tungstate and zinc silicate now used. In this connection Fig. A, reproduced from a photograph of a "modulation trace," may be of interest.† The photograph received an exposure of 1 minute at $f\,4\cdot5$, using an "Iso" 700 H and D plate (Wellington). The cyclographic wave-form photograph reproduced in Fig. B required, however, only 15 seconds' exposure under similar conditions. It is interesting to record Mr. D. W. Dye's success with the contact method

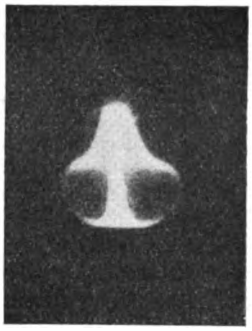

FIG. A.—Modulation trace.

FIG. B.—Cyclographic wave-form photograph.

of recording traces.‡ Using an ordinary sensitized paper, only a few seconds' exposure was necessary, and complete darkness in the room was of secondary importance.

The correction necessary to take account of the curvature of the fluorescent layer when the contact method is used is, in the case of the Western Electric oscillograph, represented by

$$y = -\frac{Y^3}{2RL_2}$$

where Y = deflection on a plane screen,
R = radius of curvature of the fluorescent screen, and
L_2 = distance from the screen to the deflector plates.

In the Western Electric oscillograph, $2R$ is about 20 cm, and L_2 is 20 cm. Then, for a deflection of 4 cm, the error introduced by the curvature is $1\cdot6$ mm, or 4 per cent. The deflection is in practice generally kept smaller, so that the error is negligible.

The authors' reference on page 1092 to my time motion does not mention a modification which makes it, I believe, as nearly linear as the low-frequency mechanical systems. In this modification, the series resistance in the neon-lamp circuit is replaced by a diode working on its saturation current. The filament current of the diode may be so adjusted that a convenient range of condenser values may be used for the frequencies concerned. The system is really a particular case, with a neon-lamp trigger, of Rogowski's time-base; the discharge of the condenser is, however, extremely rapid with the neon-lamp system due to the big increase in the current through the neon lamp. The wave-shape of the time motion is shown in Fig. C.

Messrs. J. T. MacGregor-Morris and **R. Mines** (*in reply*): The exposure figures which we quoted for the Western Electric oscillograph were for a "mixed" screen, but soon after completing our paper—that is, now more than a year ago—we heard that improvements were then being effected in the photographic

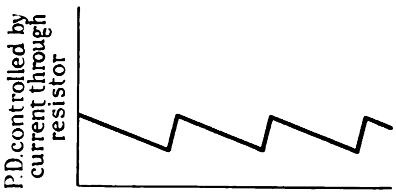

FIG. C.

power of the oscillograph, and we are glad to note the better results quoted by Mr. Kipping.

A reference is given to Mr. Dye's excellent work in the Bibliography, No. 124 (page 1107).

The curvature-correction formula given by Mr. Kipping is the limiting case for our formula on page 1087. (A slip has, unfortunately, occurred four lines above our formula, where "2 cm" should read "D cm.")

We must express our appreciation of Dr. Fleming's neat geometric solution of the problem of the use of the instrument as a high-frequency wattmeter, which appeared in the same number of the *Journal* (page 1045); and also of Dr. A. B. Wood's admirable work on a 3 000-volt instrument.

Finally, our attention has been drawn to the very recent work in America of Mr. F. R. Terroux, who uses a flat quartz plate for the end of the tube having fluorescent material on its inner surface, and takes records by pressing a photographic film flat against the outside of the quartz plate, thereby considerably simplifying the operation of recording, as well as reducing largely the exposure necessary.

We should like to take this opportunity to bring up

* Paper by Prof. J. T. MacGregor-Morris and R. Mines (vol. 63, p. 1056).
† See *Experimental Wireless*, 1925, vol. 2, p. 814.
‡ See *Proceedings of the Physical Society of London*, 1925, vol. 37, p. 158.

to date the Bibliography at the end of our paper (page 1105) by the following additions :—

J. A. FLEMING : *Journal I.E.E.*, 1925, vol. 63, p. 1045.
A. B. WOOD : *Ibid.*, p. 1046.
F. R. TERROUX : *Journal of the Franklin Institute*, 1925, vol. 200, p. 771.
K. B. McEACHRON and E. J. WADE : *Journal of the American Institute of Electrical Engineers*, 1926, vol. 45, p. 46.

DISCUSSION ON "ELECTRICITY IN MINES." *

DISCUSSION AT A JOINT MEETING OF THE SCOTTISH CENTRE OF THE INSTITUTION AND THE ASSOCIATION OF MINING ELECTRICAL ENGINEERS, AT GLASGOW, 8 DECEMBER, 1925.

Mr. F. Anslow: We must bear in mind that the figures and data given in the paper bear almost entirely on the conditions in South Wales, and those of us who have experience in that coalfield will appreciate the very different conditions which have to be met in other coalfields, particularly in the West of Scotland, so that it is impossible to take the author's figures as they stand. Taking one instance only, the author refers to refuse coal being dumped into his station, and mentions that this refuse coal has an ash percentage of 5 to 11 per cent. If many of the colliery plants with which we are concerned in the West of Scotland were supplied with coal with such an ash content we should not have much difficulty in dealing with it. Much of the refuse coal used in this district is more nearly of the order of 30–40 per cent of ash. Under certain conditions it is profitable to wash this refuse coal and so reduce the ash contents, but in other cases it cannot be done economically. At the West of Scotland collieries particularly, there is a lot of refuse coal which has to be got rid of one way or another, and the general experience now is, as it was before the war, that the easiest and cheapest way is to burn it under boilers, and, so long as all the steam required can be produced in this way, there is no particular reason in attempting to reduce the quantity burned. On the other hand, however, as soon as it is necessary to burn the higher-grade fuel in order to make up the quantity of steam required, it is necessary to improve economy and so reduce the quantity of fuel required. The question of electric or steam winders has, I think, been sufficiently considered in this and previous papers and discussions, and I would only add that I agree almost entirely with the author's diagram showing the wastage which goes on in the high-pressure end of a mixed-pressure turbine. This is, I think, not always fully appreciated in considering the 24 hours' load at a colliery, as distinct from the 6 or 7 hours' actual running of the winder, during which the exhaust steam is available for the low-pressure end of the turbine. I do not for a moment suggest that in suitable cases a combination of steam winders and low-pressure turbines is not an economical proposition, but I do say that, in view of the large capital expenditure involved, we should carefully consider everything that is involved in the scheme before deciding in favour of such a combination as against purely high-pressure steam and electric winding or other alternative schemes. The author refers to the turbine-driven Ward-Leonard generating plant for supplying power to an electric winder, as a recent development. In certain respects this is so, and I think it may be of interest if I point out that the pioneer of this plant was erected in the West of Scotland nearly 20 years ago, and I shall now show a lantern slide of the actual plant. In principle the combination referred to by the author is similar to the pioneer plant on the Clyde, with the exception that in the earlier plant the prime mover was a high-speed engine and not a turbine. This is not an important difference, the main problem in each case being to arrange a suitable governor for economically allowing the necessary drop in speed to enable the flywheel to give up its energy to meet the peak loads of the winding, and to bring the flywheel back to full speed during the intervals between the winds. It will be noted that the pioneer set consists of a high-speed engine to which is first coupled a d.c. generator operating at a constant voltage for supplying power in the ordinary way, as distinct from the variable voltage of the Ward-Leonard sets. There is then coupled a flywheel and lastly two variable-voltage Ward-Leonard generators. It will be noted, therefore, that this combination set goes further than the combination illustrated by the author, and that there is an additional problem introduced, viz. that a constant voltage should be obtained from the constant-voltage generator, independent of the variation in speed of the combined plant up to, say, 20 per cent. This problem necessitated a good deal of consideration, as it was recognized that the ordinary form of automatic voltage regulation would not meet the conditions satisfactorily, and eventually the difficulty was overcome in a comparatively simple way. A small d.c. generator is driven by means of a belt from the shaft of the combined plant. The armature of this generator is in series with the exciting field on the main generator, but in opposition to it, the result being that, immediately the speed begins to fall, the speed and therefore the voltage of the small generator fall, thus allowing an increased flow of current in the main field of the generator. This arrangement proved to be so efficient that the voltage of the main generator is maintained practically constant with a variation of speed of

* Paper by Major E. I. David (see vol. 63, pp. 521, 563 and 1129).

20 per cent, and with any variation in load from nothing to full load. Two of these plants were put into operation in 1906. A third was added shortly afterwards, and all three plants are still running, and therefore I do not see why the plant referred to in the paper should not give equally satisfactory results.

Mr. D. M. MacLeod: The author refers to the difficulty which power engineers invariably have in putting terms before colliery owners. It is almost impossible to get an approximate idea of the power requirements at many of our collieries. In the early days of the Clyde Valley development we used to get most extraordinary figures put before us of the probable demands that would be required. A favourite figure seemed to be 500 h.p., but in most cases it was found that a 100-kVA transformer would handle all that was wanted, with a good deal to spare. It might be a matter of interest to mention the development which has occurred in the mining demand during the 10 years ended 31st December, 1924. The connected load to the Clyde Valley mains in December, 1914, was 6 633 kW. In December, 1924, it amounted to 15 782 kW, an increase in that period of 9 149 kW, which shows that the application of electrical energy to the working of our coal mines is making steady and satisfactory progress.

Mr. W. Sutcliffe: Frequent mention is made of the use of synchronous motors, and one must admire the author's courage in so emphatically recommending the salient-pole machine as against the synchronous induction or the plain induction type. Personally, I think that the salient-pole machine is not used so extensively as it might be; there are many drives for which it is eminently suitable, such as motor-generator sets, compressors and centrifugal pumps, all of which can be designed for light-load starting. Its advantages over the synchronous induction motor are a larger air-gap, a higher efficiency and a more robust rotor winding, to say nothing of two slip-rings as against three or four, and also a higher excitation voltage; incidentally, my experience of very-low-voltage exciters, such as one gets with synchronous induction machines, is that they are somewhat unstable and rather susceptible to commutator troubles. In employing a salient-pole design for the input motors of his large Ward-Leonard sets, I think the author becomes a pioneer, because to the best of my knowledge this has never been done before. Hitherto, flywheel sets designed with a falling speed characteristic have been regarded as necessary for deep and heavy output winders, but we are apparently entering a new era when flywheel equalization of load is not considered necessary. Referring to the description of the Ward-Leonard sets on page 531 (vol. 63), I see that the synchronous motor is designed for an output of 3 250 h.p. at 0·8 leading power factor at full load, and I should like to know whether these machines run normally at that leading power factor. If so, what steps are taken to maintain the figure constant under variable loading conditions, apparently fluctuating from about 100 to 4 000 b.h.p. through each winding cycle? It appears to me that without some special device the motors would be excessively over-excited at times of light load, say during the interval between winds; this condition will cause a heavy current at low leading power factor to be drawn from the system, and thus seriously disturb the voltage regulation at the station, particularly if the plant capacity on the busbars were not considerably in excess of the synchronous motor load. On page 568 the author makes a casual reference to a device for automatically correcting the power factor under the variable loading just referred to, and further details of this would be of great interest, because for a small generating station contemplating the addition of comparatively large and variable synchronous load some such automatic correcting device would appear to be essential. I am greatly interested in the Lenix drives referred to in the paper, and I should be glad to hear what type of belt was found to be the most serviceable; it would appear that the belt in "zig-zagging" round two small pulleys, thus being stressed alternately on its front and back surfaces, is subjected to very severe conditions. Has the author tried a laminated belt for this drive?

Mr. D. L. Frew: There is a great difference in practice between Scotland and Wales. In Scotland, fortunately for us, we have mines that are not as dangerous as those in Wales from a gas point of view, with the result that we have developed our electrical portion of the plant more below ground than on the surface. It is the exception to see compressed-air plant in Scotland. The proportion of coal cut by machine in Wales to that in Scotland is a proof of this. In Scotland about 47 per cent of the total output is obtained by coal-cutting machines. In Wales, taking into account air-driven cutting machines, about 25 per cent is thus obtained. On page 521 the author mentions the generation of electricity from the company point of view. I think that, on the whole, electricity is probably more economically generated at collieries than at some of our power supply stations. I make this statement with some reserve, but, taking into account some figures which I got out recently, out of about 270 000 h.p. generated in Scotland only 40 000 h.p. is generated by public supply undertakings. This does not go to show that the public supply undertakings are not giving a cheap supply, but that electricity in the mining districts in Scotland has advanced more quickly than the supply undertakings could extend their lines. I think that Scotland is rather behind Wales in regard to winding. Wales has had a better opportunity than Scotland, because many of the Welsh pits in which the author is interested are modern pits, recently sunk, and of course have had experience and can lay down the most modern plant. In Scotland, mining is a very old industry, and the best fields of coal, expecially in Lanarkshire, have all been worked and laid out at a time when steam was the power used, with the result that good steam engines have been installed, and coal masters are reluctant to part with such serviceable machinery.

Mr. G. N. Holmes: The great engineering development of the Welsh pits is mainly due, I presume, to the large seams and general conditions prevailing there. Many of our pits have been working for generations and are therefore past their best, and the adoption of such heavy units as those given in the paper would be hardly applicable in their case. It would be advan-

tageous if collieries were to combine in groups and obtain electricity in bulk from one main generating station. This would prove efficient, economical and convenient. It has been stated that many collieries can generate at a lower price than some of our public supply undertakings; at the same time it has paid these collieries, in many instances, to discard their own plant and take a bulk supply. This is a fact that should bear considerably on the convenient handling of coal and also the on-cost charges of the pits.

Mr. H. A. McGuffie: I agree that it is a much better commercial proposition to burn gas under boilers than to use it in gas engines, owing to the higher maintenance cost, etc., of the gas-engine plant. I do not agree that synchronous motors are better than static condensers under certain conditions. The high efficiency and low maintenance charge of the static condenser, also the small space occupied, should not be overlooked. I have had no trouble whatsoever with static condensers, one of these, having a capacity of over 300 kVA, being in operation for approximately 16 years. In Scotland compressed air is used to a very small extent. I cannot agree with the author that the losses in transmission for compressed air and electrical power for distances up to 5 miles are equal. In every instance I have met with in Scotland the efficiency of compressed-air plants could not be compared with that of electrical plants. I cannot quite follow the author's remarks as to "reliable" supply undertakings. Perhaps, however, the position in South Wales is different from that in Scotland, where the public supplies are in every way reliable. What is the author's opinion of the latest type of electrically controlled main and reversing switches for winders as against the compressed-air type of switches mentioned in the paper? I have had a certain amount of experience with the latter but have found the maintenance charges higher if anything than in the case of the oil-immersed quick-break electrically-operated switches. Furthermore, it was found essential to place the air-break switches in a separate room or cubicle owing to the noise and flashing, etc. I cannot understand the high maintenance charges mentioned in the paper in connection with the oil-immersed reversing switches. The winders in Scotland are much smaller than those used in South Wales. I have, however, a note of the switchgear maintenance charges on a small a.c. winder of approximately 500 h.p. The cost of oil, replacements and attendance in $3\frac{1}{2}$ years has amounted to £28 10s. I agree with the author as to the inefficiency of the average colliery boiler-plant. This matter is now, however, receiving more attention. In Scotland the question has been seriously affected by the amount of low-grade fuel which has been available at the collieries. If this fuel were not burnt it would have to be dumped on the dirt hills. I should like the author to appreciate the fact that the mining conditions in Scotland are totally different from those in South Wales. Generally the electrical plant is on a smaller scale, though it is quite apparent from the latest Government returns that Scotland is well to the fore as regards the application of electric power to the mining industry. Electrical winding is now becoming more general on new installations. It is, however, a strange fact that approximately 81 per cent of the electric winders in Scotland are connected to private generating plants.

Major E. I. David (*in reply*): The coal referred to by Mr. Anslow as containing from 5 to 11 per cent of ash is washed coal, in some instances mixed with unwashed coal, but as some of the coals are very low in volatile content, being of a semi-anthracite character, it is not such an easy matter to burn them as coals with much higher ash with higher volatile content. I agree with Mr. Anslow that in every case of modification to colliery equipment the question of steam winding and mixed-pressure turbine generation has to be very carefully weighed against the all-electric equipment, and it is only when all the available factors have been given their proper value that a decision can be reached. Mr. Anslow's description of the engine-driven Ward-Leonard set is most interesting. I was under the impression that I had installed the first Ilgner set in Scotland, but this one forestalls me by several years.

In reply to Mr. MacLeod, there is a very noticeable lack of accurate information as to the power requirements of a colliery, and here again the expert is required and his services are always well worth their cost.

Mr. Sutcliffe's experience with low-voltage exciters agrees with mine, as I have already stated in the discussion on Mr. Carr's paper. With regard to the Ward-Leonard sets without flywheels, where the peak load has a reasonable ratio to the total load on the generating plant there is no object in fitting a flywheel, particularly as, owing to duplication to meet safety requirements, colliery transmission lines are usually lightly loaded. The 3 250-h.p. synchronous motor has a special exciter having one winding supplying the necessary voltage for light-load excitation of the main motor, and auxiliary windings which are controlled by the load on the two generators. Up to normal load a leading power factor varying from 0·7 to 0·8 is obtained. At overloads the power factor drops to nearly unity. The resulting variation in line voltage is negligible. With regard to Lenix drives, a laminated belt is not advisable. A solid leather two-ply belt with cemented joints has proved most satisfactory. Some of these belts have been in operation for over 30 000 hours and there is no visible depreciation.

Mr. Frew gives most interesting figures of the relative proportions of coal cut by machines in Wales and Scotland, but the mining conditions are so entirely different that machine mining is not, for many years to come, likely to increase in Wales to the extent that it has in Scotland. With regard to winding, whilst the illustrations refer to large and fairly modern mines, in many cases very appreciable economies can be effected by electrifying the winders at small, old mines. From 20 to 30 electric winders are installed on the Powell Duffryn Co.'s system at old collieries of ages varying up to 70 years. In nearly all instances they have resulted in an increased output. This also applies to Mr. Holmes's remark.

If Mr. McGuffie will refer to my remarks with regard to static condensers in the discussions on Mr. Carr's * and Dr. Kapp's † papers, he will find that my practice

* *Journal I.E.E.*, 1922, vol. 60, p. 827. † *Ibid.*, 1923, vol. 61, p. 897.

has been very similar to that which he recommends. The static condenser has a very definite and useful field and should be used to a much greater extent than it is at present. Mr. McGuffie questions my figures for losses in air transmission but puts forward no figures of his own. I should be very pleased to show him electric transmission lines running in parallel with compressed-air transmission mains where the loss in the air transmission main is less than that in the electric transmission lines, including the step-down transformers. The electric transmission is at 11 000 volts and the air transmission at 80 lb./sq. in. He proceeds to state that the efficiency of compressed-air plants cannot be compared with that of electrical plants. This is an entirely different question from that of transmission. My contention is that air can be transmitted economically for considerable distances as long as the mains are designed on Kelvin's or other practical formulæ. The method which is employed, and for which I am responsible, is fully described in Mr. E. L. Harris's paper before the South Wales Institute of Engineers and at the Empire Mining Congress.* Mr. McGuffie's experience of reversing switches is, he states, on small winders only. He will find that up to 500 h.p. I recommend oil-immersed switches; there appears to be a critical figure above which oil-immersed switches depreciate very rapidly. The switches referred to were on a 1 150-h.p. winder with a peak load of approximately 2 000 kW. The compressed-air-operated switch is much smoother in operation than the electrically-operated switches and extremely little maintenance is required. I can assure Mr. McGuffie that I appreciate the difference in mining conditions in Scotland and South Wales and I specifically state that my paper refers particularly to conditions in South Wales. At the same time, the discussion at the various Centres has shown that the whole mining industry has much in common and I trust that the published discussion will be found of interest and value to mining engineers all over the country.

* *Journal of the South Wales Institute of Engineers*, 1924, vol. 29, p. 619; also *Proceedings of the Empire Mining Congress*, vol. 2, p. 276.

ADDRESS TO THE LONDON STUDENTS' SECTION

By Lieut.-Col. K. Edgcumbe, R.E. (T.A.), Vice-President.

"SOME CONTROVERSIAL PROBLEMS."

(Abstract *of Address delivered* 13*th November*, 1925.)

The problems which I have in mind are not electrical problems; they are not even engineering problems. They are economic problems. Of such, one transcends all others in importance at the present moment, and that is unemployment. I am convinced that this unemployment, or the dread of it, is at the bottom of the majority of our social and political troubles.

Trade has, from the earliest times, been subject to waves of prosperity and of depression. We had our boom in 1919–20 and are now suffering from the reaction. But there must be something more in it than that, since we are about the only nation in the world which is now faced with the unemployment problem. The cause must be sought in the peculiar position of this country, compared with practically all others. It is common knowledge that the British Isles are so densely populated that they cannot possibly produce enough food to support their population: in fact, two-thirds of all the food we consume comes from abroad.

All this imported food has to be paid for. Now it is obvious that we cannot go on sending gold abroad, and, even if we could, people would not want it, so that we are bound to export goods in exchange for our imports. Practically the only raw material which we can export is coal, and the demand for that commodity has fallen off enormously. We are reduced, then, to exporting manufactured goods, and as a result nearly 30 per cent of all the work turned out here must be for export, so that, somehow or other, we have got to find customers abroad for our manufactured goods; and that to the tune of some £600 000 000 per year. Now it is obvious that we shall only find purchasers if we are in a position to supply them with what they want and at a competitive price.

This price question is the difficulty. For better or for worse, the costs of production in this country are high compared with what they are in nearly all other countries. Taxes are high, rates are high, wages are high, working hours are short and trade-union practices are restrictive. The result is that we cannot find foreign customers for the goods we turn out.

Before the war about 35 out of every 100 workers were engaged in manufacturing for export. Nowadays, our exports have fallen to something like three-quarters of their pre-war quantity, so that 9 fewer workers out of every 100 can be so employed, i.e. there is, under this head, a decrease in employment of 9 per cent, a figure which is not far from the unemployment percentage at the present moment. Which goes to prove, if any proof were necessary, that it is in increased exports that we must look for salvation. If our export industries fail, we are done.

Now it is obvious that employment depends almost solely upon the value of goods manufactured, no matter whether for export or for home consumption, and has no direct connection with the national "balance of

trade" as it is called. In fact, it is quite possible for a country, like England, to be externally solvent and yet to have severe unemployment, and for another to be in financial straits and yet to have little or no unemployment. But even if looked at from the hard and inhuman point of view of the Victorian economist, whose main concern was with the balance of trade, the country with much unemployment is at a serious disadvantage, in that the employed have to carry the unemployed, thus increasing the cost of production and, with it, the cost of living.

As to remedies. An obvious way of lessening the number of unemployed would be to drown the lot! Such a course, however sound economically, might not be popular; so that we have got to do our best to find employment for our present population, and to this end it is essential to stimulate the manufacture of commodities in this country.

How can this be done? The imports of manufactured goods last year amounted to **£300 000 000** and, of this, certainly **£200 000 000** worth could equally well have been made here. It may not be generally realized that out of every **£100** of manufactured goods, some **£80** goes directly or indirectly in wages and salaries, so that if the **£200 000 000** worth of goods had been made here, **£160 000 000** would have been so distributed. In other words, unemployment would have been reduced by some 700 000 persons.

Now it passes my comprehension to see how this can be anything but good for the country, and yet your doctrinaire economist will tell you that it makes no difference whether you import an article or whether you make it at home, because if you import it, it leaves the man who would otherwise have made it, free to make something else, which can, in its turn, be exported to pay for the import. It looks so simple, but such an argument presupposes that a man who has been brought up to one trade can change over to another forthwith.

Apart from this difficulty, the argument may have been perfectly sound 50 years ago, when foreign countries manufactured but little, this country being "the workshop of the world," and when, moreover, the law of supply and demand was allowed free play (with somewhat disastrous results, be it said). In those days, if the price of an article was too high to enable it to be sold abroad, wages fell automatically, until the cost of manufacture was low enough for it to find a market. In the same way, if there was unemployment, due to manufacturing costs being too high for a market to be found, wages dropped or working hours lengthened and the cost of manufacture fell until a market was obtained. In this way, although there were often periods of severe depression, they soon righted themselves. Nowadays, however, the position is quite different; wages are fixed on some purely arbitrary basis, and hours of labour likewise. As a result, the cost of production does not adjust itself automatically to the "world price"—and we have 1¼ million unemployed.

One man will say that production costs are high because the cost of living is high, whilst another maintains that the cost of living is high because production costs are high. Both are right. It is a vicious circle, from which it is extremely difficult to break away. In my view, the most feasible method of so doing, and thereby reducing the cost of living, is either for one and all to work a little harder, or to improve manufacturing methods. If everyone would agree to work half an hour a day longer, it is my firm belief that all weekly earnings could be increased by at least 5s.; that the cost of living would come down considerably, and that at the end of a few years the unemployment problem would have practically disappeared.

Dr. Fleming recently gave an arresting example of what a quite insignificant increase of output might mean. He showed that if it were possible to increase the output of our coal-fields by only 5 per cent, the extra coal so produced would generate as much electrical energy as all the water-power plants in Switzerland and Sweden put together. The 5 per cent would represent less than half an hour per day extra work on the part of the miners, or it could be got, one would imagine, by the introduction of a little more machinery into the pits.

Of course the nationalization of industry has long been a favourite panacea for all our ills. It is most unfortunate that this question, like that of free trade, should have become a political one, since unbiased discussion of either problem is well-nigh impossible. We are engineers, however, and not politicians, so that we can look at the matter from a practical standpoint. What, then, are the claims made for nationalization? It is usually stated (although the connection with nationalization is not clear) that the distribution of wealth is unequal—which no one will deny—and that the distribution is arbitrary and unfair—whether this is true or not, we need not now stop to consider. One of the professed aims of nationalization is to raise the general standard of living by removing this supposed anomaly, and it is of great interest to inquire what the result of such an attempt would be. One method of equalization that has been suggested is to issue a decree that all money in excess of say **£5** per week per family should revert to the State, and go towards swelling the incomes of those families who are in receipt of less than **£5** per week.

Sir Josiah Stamp, the eminent economist, has recently made a computation of the result of such a policy. He puts the income available for distribution (i.e. the amount taken from those whose incomes exceed **£5** per week) at **£1 000 000 000** per annum, from which sum must obviously be deducted the amounts which are at present paid in rates, taxes, etc., by those having incomes in excess of **£5** per week. This comes to about **£450 000 000**, so that the available surplus drops to **£550 000 000**. The next question to be considered is the provision of capital for the future. It is obviously of vital importance that provision should be made for the building of houses, factories, ships, etc., quite apart from the question of whether they are to be owned by individuals or by the State, and such provision can only be made out of this surplus of **£550 000 000** per annum. If the same rate of capital investment is to be maintained now as was the case before the war (and no one would seriously suggest that the provision of new buildings, etc., could safely be made less than at that

time—in fact, rather the reverse), this would mean the putting aside of about £500 000 000 each year, so that the surplus now available for distribution is reduced to £50 000 000. This distributable surplus would have to be divided amongst the 11 million families who at present receive less than the suggested £5 per week. A simple calculation therefore shows that the increase in income for each family would amount to something under 2s. per week. Sir Josiah Stamp states quite frankly that a large margin of error is inevitable in a calculation of this kind. He gives reasons, however, for believing that, after making all possible allowance for such errors, the ultimate increase per family must lie between nothing and 5s. per week.

The figures which I have quoted seem to me to be well worthy of study. To the man in the street, who has been led to believe that there is, somewhere or other, an almost inexhaustible " widow's cruse " full of money if only it can be tapped, they will come as a severe shock; but to the engineer, who is accustomed to averaging out the peaks of a curve, they will be quite understandable. For, after all, rich men, like mountain peaks, are numerically insignificant. It is easy to pull them down, but by so doing we shall only raise the general level of wages by a few pence, and we shall have gone a long way towards destroying a civilization which it has taken thousands of years to build up.

As a humdrum alternative, I cannot help pointing out that to increase the working week from 47 to 50 hours would be a much more effective way of increasing the earnings of everybody, and would do so to a much greater extent.

The second contention of those who favour nationalization is that the productiveness of the workers would be increased in two ways. Firstly, all would be employed (although how the goods made are to be sold at a non-competitive price is not explained); and secondly, if all were working for the community, instead of for individuals, they would work with a swing and a gusto, at present lacking. Those who advance this argument seem to forget that in the municipal worker we have long had an example of men who are working solely for the community, but I have looked in vain amongst them for signs of that swing or that gusto which we are led to expect.

All will agree that what is really wanted is some *rapprochement* between employers and employed. The employers are quite ready, I am sure, and so are the vast majority of the employed; but, unfortunately, the latter are not free agents. What is the use of continually advocating external good will if we are all the time to be faced with internal ill will, and that between two sections of the community, neither of whom can get on without the other. There are, however, hopeful signs that the absurdity of this position is being more and more widely recognized.

To sum up the points which I have tried to make. (1) Let us reduce unemployment by insisting on the purchase of British-made goods, thus keeping at least 90 per cent of their value in this country. (2) Lower the cost of living, not so much by lowering wages and salaries, as by producing more, either by working harder or by employing more machinery and better methods. (3) Don't expect Governments to perform miracles. The State already " coddles " us far too much; the slacker loses all sense of responsibility, whilst the worker has to " foot the bill." (4) Don't be pessimists; do, please, be optimists! The Old Country is not done yet by a very long way, although her enemies, within and without, would dearly like to think so.

What is wanted, it seems to me, is a little more enthusiasm, a little more pulling together, a little less talk of rights and a little more of duties :—In the words of Daniel Webster, " a little more keenness to develop the resources of our land, call forth its powers, build up its institutions, promote all its great interests, and see whether we also, in our day and generation, may not perform something worthy to be remembered."

PROCEEDINGS OF THE INSTITUTION.

731st ORDINARY MEETING, 22 OCTOBER, 1925.

(Held in the Institution Lecture Theatre.)

Mr. W. B. Woodhouse, Past-President, took the chair at 6 p.m.

The minutes of the Annual General Meeting held on the 7th May, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The Chairman announced the result of the ballot to fill the vacancies on the Council (see vol. 63, page 843), and a vote of thanks was passed to the scrutineers of the ballot.

Lists of donations to the Benevolent Fund (see vol. 63, pages 615, 721, 844, 931 and 1044) were taken as read and the thanks of the meeting were accorded to the donors.

The Premiums and Scholarships (see vol. 63, pages 574, 613 and 721) awarded during the session 1924–25 were presented by the Chairman to such of the recipients as were present.

The chair was then vacated by Mr. Woodhouse and taken by **Mr. R. A. Chattock,** President, amid applause.

Mr. Roger T. Smith: It was said of the life of King Charles I that nothing became that life so well as the manner in which he left it. Of Mr. Woodhouse, our retiring President, it can be said that nothing throughout his professional life became him so well as the manner in which he has conducted, during the last year, the affairs of this great Institution. I can assure the members that presiding over this Institution, although it has many compensations, is no light burden. The burden is very real, and it does not get lighter as years go on, as the arms of the Institution stretch further throughout the country. Fortunately, owing to the wise policy of several of our Hon. Treasurers and of the Council, there is no financial anxiety, but the other burdens are so great that those whose business it is to suggest a President to the members for election each year have, since the war, hesitated to suggest anyone who had not at least his work in London, even if he did not live in London. It is an added distinction to the conduct of the office of the chair which Mr. Woodhouse is now vacating that he, living 185¾ miles by the shortest route from London, has yet been able to discharge the duties with such singular success. The precedent so set has resulted in my old friend, Mr. Chattock, who lives more than 100 miles from London, being elected this year as President. I move with great pleasure: "That the best thanks of the Institution be accorded to Mr. W. B. Woodhouse for the very able manner in which he has filled the office of President during the past year."

Dr. A. Russell: I have great pleasure in seconding the resolution so ably proposed by Mr. Roger Smith. I am sure that the members will agree with me that we have never had a more kindly and dignified President than Mr. Woodhouse. As Chairman of the Council he was ideal. Members of the Council often do not see eye to eye, but after Mr. Woodhouse had summed up the discussion there was always in sight some decision that would please everybody. We are specially indebted to him for the many addresses he gave to the Local Centres. Apart from their literary excellence, they possessed that local flavour which was so appreciated by his audience. I have great pleasure in seconding the resolution.

The resolution was then put to the meeting by the President and carried with acclamation.

Mr. W. B. Woodhouse: I thank the members very much for their vote of thanks, and especially Mr. Roger Smith and Dr. Russell for the very kindly way in which they put it to the meeting. I have had a very pleasant year of office, very largely because I have had the support and help of a very able Council, and also because we felt in the Council that we had the support of the general body of members. I feel that the Institution is progressing in the right way. I believe that it is becoming more and more useful to its members and to the industries in which they are engaged. I was particularly impressed during my year of office with the strength of our Local Centres, with the enthusiasm, and with the time and thought put into the organization of the meetings there. I believe that they are a great source of strength to the Institution, and a growing one. I hope and believe that my successor and friend, Mr. Chattock, will have an equally happy year of office, and I feel confident that under his guidance the Institution will continue to progress as it has done in recent years.

The President then delivered his Inaugural Address (see page 1).

Mr. C. P. Sparks: The electricity supply industry started over 40 years ago, and this is the first occasion on which the Institution has seen fit to select as its President the engineer and manager of a municipal undertaking. Mr. Chattock is an old friend of so many here to-night that it is a matter of historic interest to be able to congratulate him on being the first municipal engineer to become President of this Institution. I think, myself, that the Institution has missed something in waiting so long, when we see that the invested funds of the municipalities in our industry now exceed £120 000 000. I much appreciate the opportunity of being the first to congratulate our President on his interesting Address and have pleasure in moving: "That the best thanks of the Institution be accorded

to Mr. R. A. Chattock for his interesting and instructive Presidential Address and that, with his permission, the Address be printed in the *Journal* of the Institution."

Dr. W. M. Thornton: I have much pleasure in seconding this vote of thanks to the President for his most able and informative Address, so full of practical wisdom. The great undertaking over which Mr. Chattock rules in Birmingham is one of the most progressive in the country. We convey to him our heartiest good wishes for a successful year of office.

The resolution was then put to the meeting by Mr. Woodhouse, Past-President, and was carried with acclamation. After the President had briefly replied, the meeting terminated at 7 p.m.

48TH MEETING OF THE WIRELESS SECTION, 4 NOVEMBER, 1925.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Past-Chairman, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 3rd June, 1925, were taken as read and were confirmed and signed.

A list of Premiums awarded by the Council for papers before the Wireless Section during the Session 1924–25 (see vol. 63, page 613) was read.

The chair was then vacated by Mr. Shaughnessy and taken by Major Binyon amid applause.

A vote of thanks to Mr. Shaughnessy for his services as Chairman of the Wireless Section during the past two sessions was proposed by Prof. C. L. Fortescue, seconded by Mr. C. F. Phillips, and carried with acclamation.

Major B. Binyon, O.B.E., M.A., Chairman of the Wireless Section, then delivered his Inaugural Address (see page 83).

A vote of thanks to Major Binyon for his Address, proposed by Admiral Sir Henry Jackson, G.C.B., K.C.V.O., F.R.S., and seconded by Mr. E. H. Shaughnessy, O.B.E., was carried with acclamation, and the meeting terminated at 7.45 p.m.

732ND ORDINARY MEETING, 5 NOVEMBER, 1925.

(Held in the Institution Lecture Theatre.)

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 22nd October, 1925, were taken as read and were confirmed and signed.

The President announced that the Council had elected Dr. S. Z. de Ferranti to be an Honorary Member of the Institution.

Messrs. O. P. Moller and C. H. D. Lang were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:

ELECTIONS.

Member.

Gray, James Gordon, D.Sc.

Associate Members.

Badger, William Herbert.
Bartlett, Sydney, B.Sc.
Child, Henry Adair, B.Eng.
Dixon, Joseph Laurence, B.Sc.
Jamieson, Charles Dudson.
Jarrett, Austin Yorke.
Lyons, Henry Montagu.
Vernon, Robert Jackson.

Graduates.

Akister, Frederick.
Barnett, Reginald Hugh.
Bentley, Francis Ecroyde.
Bruges, William Ernest.
Cardew, Reginald William, Captain, R.E.
Cleary, Herbert.
Clyma, Hugh Palmer.
Conway, George Harold.
Cowen, Alan Biddulph.
Dawson, William James.
Eales, Alfred Billington.
Golding, James.
Jacobi, Erhard.
Kingston, Alfred Thomas.
Knowlson, John McKerrow, B.A.
Leary, John Francis.

Graduates—continued.

Lobo, Alfred.
Manyam, Venkataram Subrah.
O'Brien-Malone, Patrick Joseph.
Ramaswami, Kuppuswami.
Ranganatham, Mayavaram Krishnasami, M.E.
Rees, Cyril Mostyn.
Rogans, Thomas Harold.
Schulitz, Walter Hans, B.Sc.
Staygle, Edmund George.
Stredwick, Stephen Bertie.
Teather, Reginald Herbert, B.Sc.
Toplis, Leslie George.

Students.

Bacon, Anthony Walter, B.A.
Ballantine, James Rogers.
Barrell, Frank.
Beer, Jack.
Bell, George Barrett.
Benn, Leslie Robert.
Bishop, William Russell.
Boardman, Archibald Richard.
Boyne, Samuel Noel.
Briggs, Arthur.
Carter, Robert Owen.
Clarke, George Green.
Collins, Wilfred John.
Crawshaw, William Henry.
Currey, John Heylyn.
Davies, Harold Charles.
Deglon, Cedric Russell.
De Larue, Serge.
Desai, Shantilal Ranchhodbhai.
Dixon, Douglas Leslie.
Ely, Raymond Edward V.
Erskine, Alexander.
Easterbrook, Charles Bertram.
Fearnley, Gilbert Leslie.
Gill, Thomas, B.Sc.
Gilroy, Gordon Leslie.
Goffer, Norman Frank.
Gordon, David Alexander, B.Sc.
Greasley, George.
Griffiths, Cecil.
Gubbins, John Bryan M.
Hall, Edmund Burbidge.
Harbour, Joseph Richard.
Harris, Frederick Henry.
Harries, Merfyn Aeiron.
Heale, John Ernest A.
Hinchliffe, Donald.
Ingamells, George Harry.
Jaffe, Charles Cecil.

Students—continued.

James, Gwynne Frederick.
Jordan, Edwin Horace.
Kerr, Douglas Ramsdale.
Leith, Allan Ramsay.
Lyne, Edward Aubrey.
Macmaster, Malcolm Morrison.
McNicholl, John Gerard.
Milmore, Andrew Skillen.
Mitchell, Harold Edward.
Mozumdar, Dhirendra Nath, B.Sc.
Newstead, Dudley Francis.
Noel, Roger Joseph M. L., B.Sc.(Eng.).
O'Reilly, Christopher B. E.
Purkins, Leslie.
Rhys-Jones, John Emyr.
Ritchie, Roderick MacIntosh.
Russell, James.
Shafi, Sheikh Mohd.
Shields, Douglas.
Spence, Herbert William.
Starkey, Albert Ernest.
Stewart, Ian.
Stewart, James Charles.
Sutton, Percy William.
Talling, Frank Charles.
Taylor, Cecil William.
Thomas, Noel, B.Sc.
Topliss, Maurice Joseph.
Tyson, Lubbock Temple I.
Uden, Frank Arthur.
Ullah, Nimat.
Vincent, Stephen Clement.
Watson, Richard.
Weller, Bertram Frederick.
White, Howard Sydney.
White, Joseph John.
Whitehead, Stanley, B.A.
Williams, Hugh Laity.
Winwood, William.
Woods, John.

TRANSFERS.

Associate Member to Member.

Brydon, Sydney, D.Sc.
Carey-Thomas, Hubert Carey, Captain, R.C.S., B.A.
Lunn, Alfred Lawrence.
Pinkney, William Ferrier T.
Schuster, Leonard Walter, M.A.
Scott, George Smith.
Thomas, John Henry.

Associate to Member.

Morshead, Leslie Robert.

Graduate to Associate Member.

Brown, Vance Auberon, B.Sc.Tech.
Chapman, Sydney Ronald, M.Sc.
Lloyd, William Francis, B.A.
Messent, Keith Santo, B.E.
Steele, William Herbert.

Student to Associate Member.

Ashmore, Joseph.
Burt, Brian Morton, B.Sc. Tech.
Reyner, John Hereward, B.Sc.
Walker, Charles Ian B.

Student to Graduate.

Barton, Thomas, B.Sc. Tech.
Beard, James Reginald, B.Sc.
Collyns, Charles Henry A.
Johnson, Arthur.
Lane, Gerald Nassau S.
Mather, Gilbert, B.Sc. Tech.
Yates, Joseph Henry.

A list of donations to the Benevolent Fund (see vol. 63, page 1147) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Mr. P. Dunsheath, Member, entitled "Dielectric Problems in High-Voltage Cables" (see page 97) was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

733RD ORDINARY MEETING, 19 NOVEMBER, 1925.

(Held in the Institution Lecture Theatre.)

Sir James Devonshire, K.B.E., Vice-President, took the chair at 6 p.m. in the absence of Mr. R. A. Chattock, President.

The minutes of the Ordinary Meeting held on the 5th November, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A lecture by Mr. T. Carter, Member, entitled "The Engineer: His Due and His Duty in Life" (see page 193), was read and discussed. On the motion of the Chairman a vote of thanks to the lecturer was carried with acclamation, and the meeting terminated at 8.15 p.m.

49TH MEETING OF THE WIRELESS SECTION, 2 DECEMBER, 1925.

(Held in the Institution Lecture Theatre.)

Major B. Binyon, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 4th November, 1925, were taken as read and were confirmed and signed.

A paper by Mr. H. A. Thomas, M.Sc., entitled "The Performance of Amplifiers" (see page 253), was read and discussed. On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 8 p.m.

734TH ORDINARY MEETING, 3 DECEMBER, 1925.

(Held in the Institution Lecture Theatre.)

Mr. R. A. Chattock, President, took the chair at 6 p.m.

A vote of condolence with His Majesty the King and the Royal Family on the death of Queen Alexandra was passed, the members standing in silence.

The minutes of the Ordinary Meeting held on the 19th November, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 92) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Professor S. Parker Smith, D.Sc., Member, entitled "An All-Electric House" (see page 289), was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 8.5 p.m.

735TH ORDINARY MEETING, 17 DECEMBER, 1925.

(Held in the Institution Lecture Theatre.)

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 3rd December, 1925, were taken as read and were confirmed and signed.

A paper by Mr. C. E. Webb, B.Sc.(Eng.), Associate Member, entitled "The Power Losses in Magnetic Sheet Material at High Flux Densities" (see page 409), was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.25 p.m.

50TH MEETING OF THE WIRELESS SECTION, 6 JANUARY, 1926.

(Held in the Institution Lecture Theatre.)

Major B. Binyon, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 2nd December, 1925, were taken as read and were confirmed and signed.

A paper by Lieut.-Col. K. E. Edgeworth, D.S.O., M.C., Royal Signals, Associate Member, entitled "Frequency Variations in Thermionic Generators" (see page 349), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.40 p.m.

736TH ORDINARY MEETING, 7 JANUARY, 1926.

(Held in the Institution Lecture Theatre.)

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 17th December, 1925, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The following lists of donations were taken as read and the thanks of the meeting were accorded to the donors.

Library: Air Ministry; American Railway Association; I. Aprihăneanu; Association of Municipal Electrical Engineers (Union of South Africa); Astronomer Royal; "Australasian Electrical Times"; Prof. F. Bacon, M.A.; Messrs. J. B. Baillière et Fils; Messrs. H. C. Baird & Co., Inc.; Messrs. E. Benn, Ltd.; Messrs. Blackie & Son, Ltd.; J. G. Blanco; Board of Education; British Aluminium Co., Ltd.; British Engine, Boiler & Electrical Insurance Co., Ltd.; British Engineering Standards Association; British Science Guild; T. M. Carey; C. Cater; Messrs. Chapman & Hall, Ltd.; Chief Inspector of Factories; Messrs. E. Chiron; Comité International des Tables Annuelles de Chimie, de Physique et de Technologie; Messrs. Constable & Co., Ltd.; Messrs. Craven Brothers (Manchester), Ltd.; Department of Scientific & Industrial Research; Electricity Commissioners; M. A. El-Sayed; Empire Mining and Metallurgical Congress; Prof. J. A. Fleming, M.A., D.Sc., F.R.S.; E. Garcke; G. Giorgi; P. Good; W. Greenwood; M. D. Hart; Dr. W. H. Hatfield; C. C. Hawkins, M.A.; Institution of Engineers, Australia; Institution of Railway Signal Engineers; J. T. Irwin; Japanese Electrotechnical Committee; Prof. A. E. Kennelly, D.Sc.; J. W. Lieb; Sir Oliver Lodge, D.Sc., F.R.S.; Marconi's Wireless Telegraph Co., Ltd.; C. W. Marshall; R. L. Morrison; D. Murray; New Zealand Public Works Department (Chief Electrical Engineer); P. O. Pedersen; Royal Albert Observatory, Mauritius; A. Russell, M.A., D.Sc., LL.D., F.R.S.; Schweizerischer Elektrotechnischer Verein; Signals Experimental Establishment, Wool-

wich (Chief Experimental Officer); Prof. S. P. Smith, D.Sc.; W. W. Smith; Spolku Československých Inženýrů; Messrs. E. & F. N. Spon, Ltd.; Messrs. J. Springer; A. L. Stanton; T. Stevens; Surveyor-General of India; Messrs. Tata, Ltd.; W. T. Taylor; W. J. Thorrowgood; Union des Syndicats de l'Electricité; Verlag des Vereines Deutscher Ingenieure; C. H. Yeaman.

Benevolent Fund: (See list of Donations on page 192.)

Captain P. P. Eckersley, Member, then delivered a lecture entitled "The Past, Present and Future Development of Wireless Telephony, and the lecture was followed by a discussion.

On the motion of the Chairman a vote of thanks to the lecturer was carried with acclamation, and the meeting terminated at 8 p.m.

INSTITUTION NOTES.

Discussions at Meetings.

The Council are especially desirous that the remarks of speakers at the meetings of the Institution should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a "Discussion" and that contributions in manuscript should more appropriately be sent to the Secretary for publication in the *Journal* as communicated remarks. It is therefore hoped that those taking part in discussions will confine themselves as far as possible to the use of notes only.

Model Form of General Conditions of Contract (Home).

Clause 37 (Regulations of Local Authorities) of the September, 1921, edition of the Model Conditions "A" for Home Contracts, with erection, has been amended by the Council to make it clear that the Regulations and Bye-Laws with which the Contractor shall conform are those which the Local or other Authorities are authorized by Statute to make. In Clause 37 of the new edition (revised January, 1926), the words "which they are authorized by Statute to make and" have been inserted after the word "Authorities." The new edition in all other respects is similar to the old edition.

National Certificates and Diplomas in Electrical Engineering.

The following colleges, etc., have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Ordinary Grade Certificates (Senior Part-time Course):

Sunderland Technical College.

Approved for Higher Grade Certificates (Advanced Part-time Course):

Coventry Municipal Technical Institute.
Sheffield University (Department of Applied Science).

Approved for Ordinary Grade Diplomas (Senior Full-time Course):

Swansea Municipal Technical College.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 January–25 February, 1926:—

	£	s.	d.
Adkins, H. (Coventry)		2	6*
Aitken, T. A. (Manchester)		10	6
Aitken, W. (London)	1	1	0
Alexander, T. R. (Enfield)		5	0*
Allan, J. (Burntisland, N.B.)		5	0
Allan, P. F. (Newcastle-on-Tyne)	1	0	0
Amis, F. H. (Wallington)		5	0
Anderson, J. (Glasgow)		10	6
Anderson, W. Y. (Birmingham)		5	0*
Andrews, E. (Barnsley)		10	6
Andrews, R. (S. Shields)		3	6
"Anonymous"		7	6
"Anonymous"		5	0
"Anonymous"		3	6
Arthur, J. W. (Reading)		10	0
Ashton, A. L. (London)		8	6
Aylmer, J. (Wilmslow)		10	0
Babb, H. C. (Musselburgh)		10	0
Baggaley, C. F. (Mansfield)		2	6
Baldwin, L. L. (Ahmedabad, India)		8	6
Banner, E. H. W. (Wembley)		5	0
Barnett, W. A. (West Bromwich)		5	0*
Barrow, L. L. (Liverpool)		15	0
Bartlett, H. V. (London)		10	0
Basil, D. A. (Stafford)		3	6
Bates, D. O. (Tongshan, N. China)		10	0
Baxter, W. M. (Bombay)		5	0
Bayne, A. E. (Edinburgh)		8	6
Bedingfield, W. K. (Birmingham)		5	0*
Bell, D. E. (St. Helens)		15	0
Bell, H. (Hull)		5	0
Bennett, A. E. C. (London)		5	0
Bennett, H. J. (Southsea)		10	6
Biederman, E. A. (Brighton)		10	0
Billingsley, F. T. (Gold Coast)		5	0
Binns, J. W. (London)		2	6
Bishop, D. H. (Dundee)		12	6

* Annual Subscriptions.

	£	s.	d.
Blackwood, J. A. (London)		15	0
Blaikie, J. R. (Bedford)		10	6*
Bose, S. N. (New York)		5	0
Bound, A. F. (London)		5	0
Bramwell, H. P. (Bradford)		10	0
Brash, W. R. (Manchester)		5	0
Brazier, C. J. H. (Castle Eden, Co. Durham)		5	0
Brewer, A. E. (Evesham)		5	0*
Bridgman, W. E. (Manchester)		5	0
Briggs, B. G. (Derby)		15	0
Brockbank, R. A. (London)		3	6
Brough, L. G. (Newcastle-on-Tyne)		10	0
Broughall, G. (London)		10	0
Brown, G. V. (Glasgow)		5	0
Brown, V. A. (Manchester)		12	6
Brown, W. (Morecambe)		2	6
Buchanan, W. McE., Jun. (Glasgow)		3	6
Bull, G. G. (Birmingham)		2	6*
Bull, M. J. (London)		5	0
Bullman, H. C. (Aberdeen)		10	0
Burdes, L. (Manchester)		5	0
Burgum, W. T. (Rio de Janeiro)	1	0	0
Bushell, H. J. (London)		3	6
Bust, F. H. (Lynn, U.S.A.)	1	0	0
Butler, A. S. (Belvedere)		2	6*
Cameron, H. G. (Enfield)		10	0
Capper, F. W. (Irlam, Lancs)		5	0
Carnegie, H. S. (London)		5	0
Carpenter, G. W. (Scarborough)		5	0
Carter, A. (London)		5	0
Carter, J. G. (London)		5	0
Cartland, R. A. (Gateshead-on-Tyne)		10	0
Catterson-Smith, J. K. (Bangalore)	1	5	0
Cave, P. W. (Liverpool)		3	6
Cavill, R. (London)		5	0
Chambers, J. L. (Glasgow)		5	0
Chamen, W. A. (Cardiff)	2	2	0
Chamen, W. F. (Llantwit Vardre)		5	0
Chaytor, A. R. (Chesterfield)		12	6
Chick, J. H. (Kandy)		5	0
Chisholm, G. G. (Glasgow)		5	0
Clack, C. W. (London)		10	0
Clewett, W. H. (Cardiff)		5	0
Clutterbuck, T. (Rickmansworth)		10	0
Colley, L. J. St. J. (London)		5	0*
Collyer, J. E. E. (Coventry)		5	0*
Collyns, C. H. A. (Edinburgh)		5	0
Colquhoun, J. B. (Glasgow)		5	0
Cook, F. A. (Newcastle-on-Tyne)		5	0
Cooper, G. F. (Wembley)		3	6
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THE POWER LOSSES IN MAGNETIC SHEET MATERIAL AT HIGH FLUX DENSITIES.

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Summary.

From an examination of the results of a number of investigators it is shown that while there is general agreement as to the validity of Steinmetz's expression ηB^x, where x is a constant index, for the hysteresis loss at flux densities up to about 10 000 C.G.S. units, there are considerable divergences between the results of different experimenters at flux densities above that value, particularly in tests on sheet material. Some find Steinmetz's law to apply closely up to the highest flux densities at which tests could be carried out, whilst others record more rapid variations of hysteresis loss with B in the region of $B = 10\,000$–$16\,000$. The extent of the departure from Steinmetz's law also varies considerably, some observers finding a maximum exponent of approximately 2·0 and others obtaining values as high as 3·2.

In the paper a series of tests, both by a.c. and ballistic methods, on a wide range of sheet materials is described. The results of this appear to confirm the increase in the exponent of B in the expression for the hysteresis loss at values of B between 10 000 and 15 000. They also show comparatively little difference between the various specimens of sheet material tested.

The construction of a new Lloyd square for tests at still higher flux densities, and a further, more detailed, series of tests, both a.c. and ballistic, on a representative specimen of each type of material, making use of this square, are then described. These tests were carried up to $B = 17\,000$ or 18 000 and, while confirming and extending the previous results of increased exponents of B for values up to 16 000, they indicate a rapid decrease in the exponent at the highest values of B employed.

(1) Introduction.

At the present time there is a marked tendency amongst designers of electrical machinery to employ higher flux densities in electrical sheet steel than have been customary in the past, and, in consequence, to demand guaranteed figures for the total power losses due to hysteresis and eddy currents at correspondingly higher densities. It is therefore a matter of increasing importance to obtain reliable and accurate knowledge of the way in which the power losses vary with the flux density at high densities, particularly in the special brands of sheet material which are now so extensively employed.

Of the two components—hysteresis and eddy currents—of which the total loss consists, the hysteresis loss is usually the more important, and is also the one concerning the law of variation of which there is more uncertainty. There is general agreement as to the validity of Steinmetz's empirical law that

$$\text{Hysteresis loss in ergs per cm}^3\text{ per period} = \eta B^x$$

where x is a constant index for any given material, having a value of approximately 1·6, for flux densities between about 4 000 and 10 000 C.G.S. units; but at higher densities surprising differences between the results of different investigators appear to exist, as will be seen from the following brief survey of some of the principal papers bearing on the subject.

(2) Summary and Discussion of Results of Other Investigators.

Before proceeding to examine these results, reference should be made to a matter of terminology, in order to avoid an ambiguity which frequently arises in the discussion of laws of variation of the form to be considered when dealing with magnetic hysteresis. P. G. Agnew,* pointed out that if in an expression of the form $W = \eta B^x$ the index, x, is not a constant, but is itself a function of B, then the methods usually employed to evaluate x, for any given range of B do not give a correct result. These methods are the determination of the slope of the logarithmic curve connecting W and B, and the solution for x of the equations obtained by substituting two pairs of corresponding values of W and B, and Agnew pointed out that when x is variable the quantity found in each case is not the true exponent, x, but the value of the function $[x + B \log B(dx/dB)]$. To this quantity he gave the name "ratio of variation," and he showed that it may be very different from the true exponent and may give very little indication as to the value of the latter. He also pointed out that the ratio of variation is in practice a much more convenient and useful quantity to employ than the true exponent, and that it has generally been used under the name of "exponent" by other investigators.

In view of this and of the fact that Agnew's term is not generally familiar, it is proposed to adopt the term "exponent" throughout this paper when referring to the quantity described by Agnew as the "ratio of variation." This use of the word is also justified by analogy with the case of a constant index, and at least for small ranges this quantity is the true exponent for a curve of constant index approximating to the actual variable-index curve.

Proceeding now to the consideration of published results bearing on the law of variation of hysteresis loss at high flux densities, the most direct treatment of the subject is that of F. Stroude, in "An Accurate Examination of the Steinmetz Index for Transformer Iron, Stalloy and Cast Iron." † From tests on rings

* See Appendix IV, (1). † *Ibid.*, (2).

of each of these materials by the method of uniformly varying flux (slow cyclic) checked by ballistic tests he concludes that the Steinmetz index is practically constant for values of B above 4 000, the values found being 1·7 for transformer iron (tested up to $B = 17\,000$), 1·66 for stalloy (up to $B = 12\,000$), and 1·82 for cast iron (up to $B = 6\,000$). It is to be noted, however, that the determination of the exponent is made from the slope of the logarithmic curve, and that owing to the compression of the curve above $B = 10\,000$ when plotted in this way the determination is not very accurate at these densities. In fact, on re-plotting the logarithmic curve on a large scale, there appears to be a distinct tendency for the exponent to increase for transformer iron to a value of about 1·9 or 2·0 between $B = 10\,000$ and $B = 17\,000$. This is confirmed if the exponent is found by solving for two points on the mean curve through the points obtained by plotting the hysteresis loss (W_H) and B. For stalloy the values found do not lie well on any smooth curve, and in any case do not extend much beyond the range for which Steinmetz's law is known to apply fairly closely.

Stroude refers to the work of a number of earlier investigators whose conclusions may be summarized as follows: Steinmetz in his original paper,* working from Ewing's results and from his own experiments using a.c. wattmeter and magnetometer methods, found a practically constant index of approximately 1·6 from $B = 2\,000$ to $B = 20\,000$. Ewing and Klaassen † from ballistic tests found that the exponent (deduced from the slope of the logarithmic curve) had a different value in each stage of the process of magnetization, changing quite suddenly from one value to another. The value was approximately 2 for very low flux densities, fell to about 1·5 in the region of high permeability, and increased again to about 1·7 at high densities.

Both these experimenters used commercial soft iron such as was used in dynamo armatures—not at that time, of course, containing silicon or other special alloying constituents. Gumlich and Rose ‡ tested rings containing various percentages of silicon by the ballistic method and also by alternating current using a Franke curve-tracer. They assumed a constant index of 1·6 and calculated the corresponding value of the Steinmetz coefficient, η, for various densities. In every case η was found to increase from $B = 10\,000$ to $B = 16\,000$, in one case by as much as 25 per cent, corresponding to an increase in the index from 1·6 to 2·4. They also found that, assuming the eddy-current loss to vary as the square of the flux density, the coefficient of the eddy-current term decreased as the flux density increased, and that the eddy-current loss appeared actually to vary as the 1·8th or 1·9th power of the flux density. Prof. E. Wilson, V. H. Winson and G. F. O'Dell § carried out ballistic tests on lohys and stalloy sheets chiefly at low inductions, but recorded a few results between $B = 6\,000$ and $B = 13\,500$. These showed a marked tendency for the exponent to rise with increase of B, particularly in the case of stalloy. With both materials, however, the exponent exceeded 2 for the range of $B = 11\,500$ to $B = 13\,500$.

* See Appendix IV, (3). † *Ibid.*, (4). ‡ *Ibid.*, (5). § *Ibid.*, (6).

Lloyd and Fisher * using the a.c. wattmeter method measured the total losses in both transformer steel and silicon steel specimens at two frequencies—30 and 60 periods per second. They separated the total losses into hysteresis and eddy-current components by assuming these to be proportional to the first and second power of the frequency respectively, and found that for both types of material the exponent tended to increase at high flux densities, obtaining values ranging from 1·8 to 2·2 between $B = 10\,000$ and $B = 12\,500$. These measurements were made with great care and covered a large variety of specimens, and the results are probably the most reliable and accurate of those quoted by Stroude.

It will be seen that the investigators to whom Stroude refers obtained very divergent results, some in agreement with those recorded in his paper but others definitely in conflict with them. Before attempting to summarize the evidence for and against the constancy of the Steinmetz index, the author proposes to refer briefly to some other investigations of interest in this connection.

Prof. F. G. Baily † using a calorimetric method deduced the hysteresis loss in a laminated sample subjected to various alternating inductions up to $B = 22\,000$. His figures indicate a gradual increase in the exponent to a maximum of about 2·4 in the region between $B = 14\,000$ and $B = 18\,000$, followed by a rapid and continuous decrease to a value slightly less than unity when B approaches 22 000. That this latter effect was not due to the H lines, which might be expected not to affect the hysteresis, becoming relatively a large proportion of B, is shown by the fact that when the curve of hysteresis loss was re-plotted to a base of intensity of magnetization $J = (B - H)/4\pi$ a similar tendency to bend over above about $J = 1\,400$ was observed. This result, which does not seem to have been noticed by other investigators, is of considerable interest in view of the similar results recorded later in this paper.

Barrett, Brown and Hadfield ‡ in their comprehensive paper on the electrical conductivity and magnetic properties of a great variety of iron alloys record ballistic tests on samples of annealed silicon iron (2·5 per cent Si), and annealed Swedish charcoal iron in which, assuming a constant index of 1·6, they found a considerable increase in the value of the coefficient η when B was raised to about 17 000. This increase amounted to nearly 20 per cent for the silicon iron, corresponding to an exponent between $B = 12\,000$ and $B = 17\,000$ of approximately 2·1.

Czepek § in the course of a comparison between the losses under rotating and alternating magnetization at various frequencies and inductions made a number of measurements of hysteresis loss by ballistic and a.c. wattmeter methods. Some of his ballistic results indicate a fairly constant index of about 1·9 for flux densities between 9 000 and 17 000, but he also records alternating-current results from which, assuming a constant hysteresis exponent of 1·6, he calculates the value of η and finds, in agreement with other investigators already quoted, that η increases considerably at high densities—in one case from 1·62 at $B = 8\,000$

* See Appendix IV, (7). † *Ibid.*, (8). ‡ *Ibid.*, (9). § *Ibid.*, (10).

to 2·22 at $B = 16\,000$. He also records in the same tests that, assuming the eddy-current losses to be proportional to the square of the frequency and the square of the density, the coefficient of the eddy-current term decreases very rapidly with increasing flux density—from 4·5 at $B = 8\,000$ to 1·84 at $B = 16\,000$.

Richter * from ballistic and a.c. wattmeter results on a series of 7 rings of soft iron sheet endeavoured to establish the law $W_H = aB + bB^2$, where a and b are constants, as giving a more accurate representation of the observed results than the Steinmetz formula. This, it will be seen, implies a continuous increase with increasing B of the exponent, which, however, can never exceed 2. His results indicate a considerably smaller deviation from a law of this form than from a law involving a constant index, but it is noticeable on some of his curves that the experimental results at high densities, say $B = 17\,000$, show an even more rapid increase of hysteresis loss than is given by Richter's law.

L. W. Wild † made a large number of measurements of total losses on lohys and stalloy sheets of various thicknesses by the a.c. wattmeter method, using several different ways of building up the test-square. The tests were made at a number of values of B ranging from 2 500 to 15 000, and at 25 and 50 periods per second. He did not separate the losses, but from his total-loss figures for any given B at two frequencies the hysteresis loss may be readily calculated, assuming the proportionality of the hysteresis and eddy-current components to the first and second power of the frequency respectively, as was done by Lloyd and Fisher in their paper referred to above. The hysteresis values thus obtained show a slightly increasing exponent above $B = 10\,000$, but the maximum value found does not exceed 2. Too much reliance must not be placed on the accuracy of these results, as the tests were made with the object of comparing the various methods of building up the square, and hence the attainment of identical conditions in each test, rather than high absolute accuracy, was aimed at.

A short note by W. J. Wooldridge ‡ on "Hysteresis and Eddy-Current Exponents for Silicon Steel" bears directly on the question at issue and gives very interesting curves showing an increase of the hysteresis exponent from approximately 1·6 at flux densities below 7 000 to 3·2 at $B = 16\,000$, and a decrease of the eddy-current exponent from 2·0 to 1·6 over the same range of B. Unfortunately, the value of the paper is much reduced as no details of the method of testing (which was a wattmeter method) or actual results from which the curves were deduced are given, but in the course of the discussion L. T. Robinson claimed to have obtained closely similar results by ballistic tests.

M. MacLaren,§ in an investigation primarily directed to finding the effect of temperature on the hysteresis loss in sheet steel, determined the hysteresis loss in samples of commercial armature steel and high silicon transformer steel at various flux densities between 6 000 and 14 000, from a.c. wattmeter measurements at 25 and 60 periods per second, employing for the separation of the losses a method based on the usual assumption as to the variation of the two components with frequency, but involving the determination first of the coefficient of the eddy-current term. He determined the true exponent at each flux density, adopting as the coefficient of the hysteresis term the value found by assuming the exponent to be 1·6 at the lowest flux density employed. Under these conditions he found a nearly constant value for the true exponent, but, as was pointed out in the discussion, if the exponent is calculated by the usual methods from his results, values decreasing with increasing flux density are obtained in most cases, particularly at high temperatures. This result, which is in contradiction to most of those already recorded, is open to doubt owing to the absence of any allowance or correction for variations in the form factor, which would be almost certain to occur under the conditions of the test.

Paglianti,* in a thorough investigation of the influence of silicon on the properties of steel, made a large number of measurements by the ballistic method of the hysteresis loss at flux densities from 7 000 to 16 000 on a series of annealed rods containing various percentages of silicon from 0·24 to 5·26. He determined for each value of hysteresis loss the value of the coefficient η, assuming an index of 1·6, and whilst he found great variations of the hysteresis, and hence of η, with changes in the percentage of silicon, he obtained in all cases very similar variations of η with B, viz. that η increased 25–50 per cent as B was increased from 7 000 to 16 000, the increase becoming particularly rapid above $B = 13\,000$. Values of the exponent between $B = 13\,000$ and $B = 16\,000$ ranged from 2·1 to 3·3.

A somewhat similar investigation of the properties of silicon-iron alloys containing various percentages of silicon was carried out by Yensen † in the course of his comprehensive study of iron and iron alloys prepared by melting *in vacuo*. His measurements were made ballistically, using the Burrows permeameter, and he also found a very high exponent of B for the hysteresis loss at high values of B, particularly in the alloys containing large percentages of silicon. For one specimen the exponent between $B = 10\,000$ and $B = 15\,000$ was as high as 3·2. Considerable doubt has been thrown, however, on the accuracy of the Burrows method of testing for such highly permeable materials, and tests on rings of the same material were found to give much lower values of the exponent, the results not departing very widely from the Steinmetz relation.

One of the most interesting papers dealing with the losses in sheet material at high flux densities is that by J. S. Nicholson,‡ on "The Magnetization of Iron at High Flux Densities with Alternating Currents." He points out that in testing total loss at high densities the chief difficulty is that, owing to the harmonics in the magnetizing current, the wave-form of induced E.M.F., even with an alternator giving a good sine wave on open circuit, becomes very distorted, and that in consequence the true maximum B may be much less than that indicated by the R.M.S. induced E.M.F. To minimize the error from this cause he adopted a

* See Appendix IV, (11). † *Ibid.*, (12). ‡ *Ibid.*, (13). § *Ibid.*, (14).

* See Appendix IV, (15). † *Ibid.*, (16). ‡ *Ibid.*, (17).

method which, although too complicated for general use, secures the elimination of the triple-harmonic component of the induced E.M.F. and of multiples thereof. To effect this he employs three similar cores, each with two magnetizing windings, one set of windings being star-connected to a three-phase supply and the other set mesh-connected to a single-phase alternator of triple frequency. Then by adjusting the phase and magnitude of the triple-frequency current until the voltage induced in three mesh-connected secondary windings and the power supplied by the single-phase machine are each reduced to zero, the third harmonic in the flux wave is eliminated and a sine wave of flux with only fifth, seventh and higher harmonics, which are usually very small, is obtained. Allowance was made for the fifth and seventh harmonics by analysing the E.M.F. waves, deducing the amplitudes of the flux harmonics from those of the induced E.M.F., and correcting the apparent value of the maximum flux density accordingly. A further correction was made for the flux in the air space within the secondary windings, using a permeability curve obtained ballistically.

The total losses in the three cores (built up of stalloy rings) were determined by measuring the three-phase input by a two-phase wattmeter at various values of the flux density (corrected as described above) and at frequencies of 15 and 22·5 periods per second. The resulting values of total losses were separated into hysteresis and eddy-current losses by the usual method based on frequency variation, and the hysteresis losses obtained were plotted logarithmically against B. The curve approximated to a straight line, indicating a constant index of about 1·58, even up to $B = 20\,500$. Prof. Baily, however, analysing the results in a somewhat different way (by calculating the eddy-current loss at each flux density from the mean value of the eddy-current coefficient, instead of using the values found from the results at that flux density only) found that the logarithmic curve connecting hysteresis loss and B was markedly convex to the axis of B, i.e. that the exponent increased with increasing B and rose to a value of approximately 3·5 above $B = 20\,000$. The results recorded in the paper thus appear to be rather inconclusive, but they seem clearly to indicate that there is no tendency for the hysteresis exponent for stalloy to decrease even at inductions as high as 20 500—a result directly contradictory to that found by Prof. Baily (see above), and, as he points out, hardly to be expected in view of the presumably constant value of the hysteresis loss when actual saturation is reached.

A recent investigation bearing on the variation of the iron losses at high flux densities is that carried out by Jouaust and Mlle Bourgoignon * at the Laboratoire Central de l'Électricité, on the losses in a large number of samples of sheet material at flux densities of 10 000 and 14 000. They used the Epstein tester as modified by Armagnat, and separated the losses by the usual method based on frequency variation, using values of total losses at 25 and 50 periods per second. They found that for some samples the exponent of B for hysteresis loss increased very much above the Steinmetz value—up to as high as 3·14 in one case—whilst for other samples considerably lower values indicating an approximation to a square law of variation with B were obtained. Their investigations appeared to show that the high values of the exponent were obtained on the group of specimens containing rather a higher percentage of silicon and having higher hysteresis loss and comparatively low permeability.

A still more recent paper bearing in some measure on the question under consideration is that by G. H. Cole * on "The Magnetic Properties of Silicon Steel in a Large Transformer." He measured the losses in the core of a 4 166-kVA single-phase transformer, built up of 4 per cent silicon-steel sheets, by both a d.c. method using the volt-second meter as described by Chubb and Spooner,† and an a.c. method involving the determination of the total losses at 25 and 60 periods per second from wattmeter measurements and from oscillograms of magnetizing current and voltage. The total losses found in the a.c. tests were separated into their two components by the usual frequency method, and the hysteresis losses thus obtained were found to be slightly greater than those given in the d.c. tests. The total losses measured on the transformer in this way were also found to be several per cent higher than those found by Epstein tests on the material of the core, the discrepancy being attributed to inferior annealing of the core material, greater pressure in the core causing increased eddy currents and, at high flux densities, fringing into the solid steel parts adjacent to the core. Although the hysteresis deduced from the a.c. measurements was slightly greater than that found from the d.c. tests, for both sets of tests the loss appeared to follow a similar law of variation with B. From the slope of the logarithmic curve connecting hysteresis loss with B a constant exponent of approximately 1·6 was deduced for values of B up to about 9 000, but above this density the exponent was found to increase continuously and more and more rapidly with B up to a value of 5 at $B = 16\,000$ (by a.c. tests) or at $B = 18\,000$ (by d.c. tests). This abnormally high value was almost certainly due in part to leakage of the flux, owing to the reduced permeability at high densities, into adjacent solid steel parts of the transformer, but it was shown that the effect of this would be inconsiderable below $B = 14\,000$, and a large increase in the exponent would therefore appear to be genuine. It is suggested that this may be due to the core material being unhomogeneous, e.g. to the presence of oxide scale.

From the foregoing résumé it is clear that experimenters on the losses at high flux densities are very far from being unanimous as to the nature of the law connecting hysteresis loss with flux density. The results obtained fall roughly into the three classes set out below :—

(1) *Results confirming Steinmetz's law,* in some cases even up to very high flux densities such as 20 000 or 22 000. In addition to the original results of Steinmetz this group includes the work of Stroude, MacLaren, Nicholson and, in spite of divergences at lower densities, of Ewing and Klaassen. In the case of Steinmetz, Ewing and Klaassen and, to some extent, Stroude, as has already been pointed out, the tests were made on

* See Appendix IV, (18).

* See Appendix IV, (19). † *Ibid.*, (20).

ordinary soft iron, not on the modern special brands of sheet material. It has also been suggested that Stroude's results are not so conclusive as they were made to appear, whilst the tests on stalloy were only carried up to $B = 12\ 000$; nevertheless, with these reservations they indicate at least a fairly close approximation to the Steinmetz law. MacLaren's results are, as previously stated, of doubtful accuracy, and in view of Baily's analysis the reliability of Nicholson's figures for stalloy, at any rate at the highest densities, is open to question. The latter's tests, however, would certainly seem to indicate that at about $B = 18\ 000$ the hysteresis index does not differ very widely from the Steinmetz value.

(2) *Results indicating an exponent of approximately 2 at high inductions.*—A large proportion of the investigators referred to above found that as the flux density was increased the hysteresis loss tended to rise rather more rapidly than was to be expected from Steinmetz's law—some obtaining an exponent of almost exactly 2, others slightly higher values such as 2·1, 2·2 or even 2·4. Of this group, the results of Wild, as has been indicated above, cannot be considered very reliable, whilst those of Wilson, Winson and O'Dell and of Baily were limited to one or two specimens. The remaining results in this class, however—those of Barrett, Brown and Hadfield, Gumlich and Rose, Czepek, Richter and Lloyd and Fisher—were obtained on a variety of specimens and do not seem open to any serious criticism as regards the accuracy of the methods employed.

(3) *Results indicating still higher exponents*, ranging up to 3 or more. Several experimenters have found, over certain ranges of B or for certain selected specimens, values of the exponent of 3 or more. These are Wooldridge, Paglianti, Yensen, Jouaust and Cole. Of these, the results published by Wooldridge are not given in sufficient detail to carry much weight, those of Yensen were obtained by a method of doubtful reliability when used for specimens with the properties of those tested by him, whilst those of Cole, being obtained on a complete transformer instead of on standard samples under exactly specifiable conditions of test, are subject to various sources of error and cannot be considered of very high accuracy. The tests of Paglianti and Jouaust, however, were carried out by standard methods and on a large number of specimens and, although the values found for the exponent differed considerably for different specimens, all gave very high values at high densities. Both these investigators obtained values of the exponent for silicon iron ranging up to about 3·2—in Paglianti's tests for the range from $B = 13\ 000$ to $B = 16\ 000$, in Jouaust's experiments for the range from $B = 10\ 000$ to $B = 14\ 000$.

Whilst, therefore, there is a large body of evidence that, at least for silicon-iron sheets, the losses increase rather more rapidly with the flux density at densities above 10 000 than at densities below that value where Steinmetz's law holds true, there is considerable disagreement between different investigators as to the extent of the deviation from the 1·6th power law, whilst two or three experimenters obtain results indicating that no such deviation occurs.

(3) Preliminary General Investigation.

Object and scope of tests.—The object of the tests to be described in this paper was to investigate the reasons for these apparently discordant results and to determine the true nature of the variation of the power losses with flux density at high densities.

In order to discover to what extent the law of variation differed for different commercial sheet materials or for different specimens of the same material, tests were made on a series of specimens provided by Messrs. J. Lysaght, Ltd., comprising samples of various thicknesses of their lohys, special lohys, high-resistance and medium-resistance grades. In each case tests were carried out at a number of values of B between $B = 5\ 000$ and $B = 15\ 000$. To provide a check against systematic errors inherent in the method of testing, parallel tests were made throughout by the ballistic and the a.c. wattmeter methods, the total power losses measured by the latter method being separated into hysteresis and eddy-current components, and the hysteresis thus deduced being compared with the static value obtained ballistically.

Methods of Testing.

(*a*) *Alternating-current tests.*—The alternating-current tests followed the usual lines of the wattmeter method of measuring total iron losses. A diagrammatic representation of the circuit for this is shown in Fig. 1, and

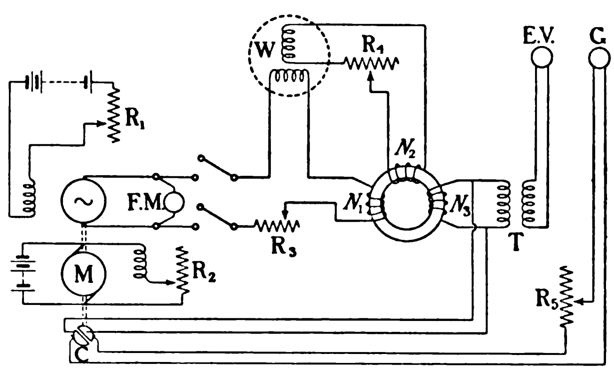

Fig. 1.—A.C. testing circuit.

the general principles of the method have been frequently described, for example, by A. Campbell * in his paper "On the Magnetic Testing of Iron with Alternating Current."

The samples used in these tests consisted of flat strips. Half of these were cut parallel and half perpendicular to the direction of rolling. They were built up into a square of the pattern due to Lloyd and Fisher † of the Bureau of Standards, Washington, but with certain modifications of their design introduced. One of the most important of these was an increase in the depth of windings to allow strips 7 cm wide to be inserted in place of the 5 cm strips used in the original apparatus. This reduces the effect on the results obtained of the higher losses in the material near the edges, caused by the cutting of the samples.

The square was wound with two primary (magne-

* See Appendix IV, (21). † *Ibid.*, (7).

tizing) coils of 640 and 160 turns respectively, and with secondary coils of 160, 80, 40 and 20 turns which could be connected to the wattmeter pressure circuit or to the voltmeters as required, to give convenient deflections. The square is indicated purely diagrammatically in Fig. 1, N_1, N_2, N_3 representing the three windings actually in use.

The wattmeter (W) was of the reflecting dynamometer type, designed to be of high sensitivity and constructed largely of marble to avoid eddy currents and thereby give accurate results at high frequencies. It had been found to be reliable up to 800 periods per second. A variable resistance (R_4) in series with the pressure coil gave a wide range of multipliers.

To determine the value of $B_{max.}$ it is necessary to measure the mean voltage induced in the secondary winding N_3, since

$$V_{mean} = 4fN_3B_{max.}A \times 10^{-8}$$

where f = frequency,
N_3 = number of turns in secondary winding,
A = cross-section of specimen.

For this purpose a Cambridge and Paul bifilar moving-coil reflecting galvanometer (G) with a high adjustable series resistance (R_5) was used, connected in series with a synchronous commutator (C).

An electrostatic voltmeter (EV), connected to the same or another secondary winding either directly or through a variable-ratio step-up transformer (T), measured the R.M.S. voltage and hence, in conjunction with the galvanometer G, gave the form factor of the induced E.M.F. wave. The voltmeter used was a low-reading Ayrton-Mather electrostatic voltmeter having a working range of 3–8·5 volts.

The source of supply was an alternator of about 5 kW rating, which gave a close approximation to a sine wave of voltage on open circuit, and the frequency and excitation of which were readily adjustable by means of the resistances R_1 and R_2. Its frequency was measured by a reed frequency-meter (FM) connected permanently to the supply terminals.

Before making any measurements the wattmeter and moving-coil galvanometer were always calibrated, as they were found to be liable to slight variations in sensitivity. To calibrate the wattmeter a direct current of exactly 1 ampere was passed through the current coil and through a standard resistance of 1 ohm, the potential terminals of which were connected to the pressure coil. A power of exactly 1 watt was thus applied to the instrument and the deflection noted. The current was then reversed and the deflection again noted, the mean of the two deflections being taken as the a.c. calibration. The galvanometer was similarly calibrated by connecting it to the potential terminals of the 1-ohm resistance. To adjust the current accurately to 1 ampere it was passed through a standard resistance of 1·0183 ohm, the P.D. on which was balanced against the E.M.F. of a Weston standard cell. This adjustment could easily be made to 1 part in 10 000.

The electrostatic voltmeter was not found to vary appreciably in its sensitivity and was therefore not regularly calibrated. It was checked at intervals on a potentiometer against a Weston standard cell.

In taking a reading, after setting the frequency to the required value, the alternator excitation was first adjusted to give approximately the desired flux density, and the brushes on the commutator were slowly rotated to give the maximum reading on the mean-voltage galvanometer. The final adjustment of this reading to the value corresponding to the desired flux density was made by means of the alternator field resistance, and the wattmeter and electrostatic voltmeter were then read.

In order to separate the losses into hysteresis and eddy-current components, readings were taken at the same values of B at two frequencies—25 and 50 periods per second. Then, if W_1 and W_2 are the total losses at frequencies f_1, f_2, for a given value of B, we may write :—

$$W_1 = \eta f_1 B^x + \xi f_1^2 k^2 B^y$$
$$W_2 = \eta f_2 B^x + \xi f_2^2 k^2 B^y$$
$$= 2\eta f_1 B^x + 4\xi f_1^2 k^2 B^y \text{ (if } f_2 = 2f_1)$$

whence

$$4W_1 - W_2 = 2\eta f_1 B^x = 2H_1 = H_2$$

if H_1, H_2 = hysteresis losses at frequencies f_1, f_2.

It is clear that this relation only holds if the form factor, k, is the same at both frequencies. This is not usually the case, particularly at high flux densities, unless special steps are taken to secure this condition. Consequently, in these tests all values of total loss were reduced to a sine wave of secondary induced voltage. For this purpose, for any values of B and frequency for which the form factor departed appreciably from the sine-wave value, a series of readings was taken with the form factor artificially varied by the insertion of series resistance (R_3) in the magnetizing circuit. Then from the above equations it is clear that for given values of B and f the curve connecting W and k^2 is a straight line, and by extrapolating to the value $k^2 = (1 \cdot 11)^2 = 1 \cdot 232$ the total losses for a sine wave of induced E.M.F. can be obtained. Using the values thus found, the above formula may be legitimately applied to separate the losses.

A correction on the apparent flux density must also be made for the flux in the air space enclosed by the secondary winding employed to measure B. Owing to the existence of this flux the value of B calculated from the mean voltage induced in the winding is too large by an amount equal to

$$H \times \frac{\text{Area of air space}}{\text{Section of specimen}}$$
$$= H \times \frac{\text{Mean area enclosed by coil} - \text{Section of specimen}}{\text{Section of specimen}}$$

The multiplying factor, being a constant for any given specimen and square, is calculated, once for all, from the known dimensions of the winding and specimen. The value of H for a given B may be taken from the permeability curve obtained ballistically, or may be directly measured by alternating current, as the results obtained by the two methods do not differ appreciably (see

Appendix 1). This correction becomes important only above $B = 10\,000$.

The values of loss obtained in the tests must also be corrected for the power lost in the instruments. The deduction to be made for the loss in the wattmeter pressure circuit is $V_W^2/R_{P.C.}$, where

$$V_W = \frac{N_2}{N_3} \times \text{R.M.S. voltage indicated on winding } N_3,$$

and $R_{P.C.} = R_4 +$ resistance of pressure coil itself.

This correction was always very small, particularly at high flux densities.

The loss in the moving-coil galvanometer circuit was in all cases negligible owing to the very high value of the series resistance R_5. It was usually less than $0 \cdot 01$ per cent of the power being measured.

Allowance for the reduction in the flux density, caused by the overlapping of the specimen and the corner pieces, was made in the way suggested by Lloyd and Fisher (loc. cit., p. 463), and in accordance with their formula, i.e. the loss per kg of material was determined by dividing the measured loss by an effective mass m given by

$$m = (m_1 + m_2)\,(1 - 1 \cdot 4c)$$

where m_1, m_2 = masses of specimen and corner pieces,
c = total length of overlapping portions of magnetic circuit, expressed as a fraction of the total length of the circuit.

When corner pieces of different material from the sample were used, an additional correction for the difference between the losses in the corner and the sample was necessary. This was made in accordance with the formula

$$W = W_1 + \frac{m_2}{m_1}(W_1 - w)$$

where W = true loss in watts per kg,
W_1 = apparent loss in watts per kg,
w = loss in corner pieces in watts per kg.

This formula, though only approximate, was sufficiently accurate provided the corner pieces resembled the test-specimen fairly closely in density, thickness and specific power loss. Where corners were cut from the same sheet as the specimen no such correction was made, it being known that the effect of the hardening due to bending of the corners was not serious.

(*b*) *Ballistic tests.*—The ballistic determinations of the hysteresis loops were made by the standard method, which is too well known to need any description. The test-set employed was the same, except for very minor alterations in certain details, as that described at length in the "Dictionary of Physics" article on "Magnetic Measurements and Properties of Materials." *

The ballistic galvanometer was a Sullivan moving-coil instrument having a resistance of approximately 600 ohms and a natural period in the field of about 10 seconds. It was fitted with adjustable shunts and series resistance to allow of the instrument being made direct-reading for B on any specimen. It was calibrated by being connected to the secondary of a Campbell inductometer in the primary of which a current of exactly 1 ampere was suddenly reversed. The current of 1 ampere was measured by a potentiometer and Weston standard cell as described above under "Alternating-current Tests."

The magnetizing current was measured by a Paul bifilar moving-coil galvanometer fitted with a range of suitable shunts and adjusted by varying a large series resistance to give direct readings of H. This instrument was calibrated by means of a Weston standard millivoltmeter with standard shunts.

The ballistic tests were made on rings of external diameter 15 cm and internal diameter 12 cm cut from the same sheets as the strips used for the a.c. measurements. It was realized that owing to the small width of these rings—$1 \cdot 5$ cm as compared with 7 cm for the strips—the effect of cutting would be much greater than on the strips, and that the values of hysteresis would, therefore, probably not be the same in both sets of tests; but as the investigation was directed rather to the nature of the variation of loss with B than to the determination of the actual values of the losses, it was thought that tests on the rings would furnish the confirmation of the a.c. results which was required.

TABLE 1.

No.	Material	Density	Measured thickness
			mm
1	Lohys	7·85	0·96
2	Lohys	7·85	0·46
3	Lohys	7·85	0·43
4	Lohys	7·85	0·37
5	Special lohys	7·80	0·45
6	Special lohys	7·80	0·40
7	High resistance	7·56	0·46
8	High resistance	7·56	0·35
9	High resistance	7·56	0·34
10	High resistance	7·56	0·32
11	Medium resistance	7·76	0·47
12	Medium resistance	7·76	0·38
13	Medium resistance	7·76	0·37
14	Medium resistance	7·76	0·37

The static hysteresis loops were plotted from the corresponding values of H and B and the hysteresis loss was calculated from their areas, measured by planimeter, in the ordinary way and expressed in watts per kg at 50 periods per second.

Results obtained.—A complete list of the materials tested is given in Table 1. From the sheets of each material, sets of strips and rings, for a.c. and ballistic tests respectively, were cut, as described above. The former were in each case denoted by the number of the material and the letter A, the latter by the number and the letter B.

As an example of the a.c. results obtained, the com-

* See Appendix IV, (22).

plete results for specimen 4A are given in Table 2. It will be seen that up to $B = 12\,000$ the form factor, k, of the wave of induced E.M.F. was practically that for to the apparent values of B is shown in Table 2A, the values of H being derived from the permeability curve shown in Fig. 2.

TABLE 2.

A.C. Results on Specimen 4A.

Mass $m_1 = 1\,232$ grammes. Cross-section of specimen, $A = 1{\cdot}569$ cm². Mass of corners, $m_2 = 66$ grammes. Overlap at corners = 4·5 mm. Effective mass, $m = 1\,229$ grammes. Magnetizing turns, $N_1 = 640$. Secondary turns (wattmeter), $N_2 = 160$.
Section of secondary coil = 20 cm², therefore correction for air flux $= [(20 - 1{\cdot}569)/1{\cdot}569]H = 11{\cdot}8\,H$.

$B_{max.}$ (apparent)	Voltmeter turns, N_3	V_{mean}	$V_{R.M.S.}$	k	k^2	Total watts (corrected)	$\frac{\text{Watts}}{\text{kg}}$	$B_{max.}$ (corrected)
			Frequency f = 25 periods per sec.					
5 000	80	0·628	0·696	1·108	1·228	0·468	$0{\cdot}38_1$	4 980
10 000	40	0·628	0·698	1·111	1·234	1·514	$1{\cdot}2_3$	9 960
12 000	40	0·753	0·841	1·116	1·245	2·175	$1{\cdot}7_7$	11 930
14 000	20	0·439	0·503	1·145	1·312	3·090		
			0·525	1·198	1·435	3·141		
			0·572	1·303	1·696	3·253		
			Sine wave	1·110	1·232	3·058	$2{\cdot}4_9$	13 880
16 000	20	0·502	0·619	1·233	1·520	4·328		
			0·693	1·381	1·906	4·524		
			0·762	1·517	2·301	4·727		
			Sine wave	1·110	1·232	4·181	$3{\cdot}4_0$	15 730
			Frequency f = 50 periods per sec.					
5 000	40	0·628	0·696	1·108	1·228	1·114	$0{\cdot}9_1$	4 980
10 000	20	0·628	0·698	1·111	1·234	3·651	$2{\cdot}9_7$	9 960
12 000	20	0·753	0·839	1·115	1·243	5·181	$4{\cdot}2_2$	11 930
14 000	20	0·879	1·003	1·140	1·299	7·291		
			1·038	1·180	1·394	7·419		
			1·085	1·235	1·524	7·658		
			Sine wave	1·110	1·232	7·179	$5{\cdot}8_4$	13 880
16 000	20	1·004	1·213	1·208	1·459	10·23		
			1·375	1·369	1·874	11·00		
			1·548	1·542	2·378	12·00		
			Sine wave	1·110	1·232	9·80	$7{\cdot}9_7$	15 730

a sine wave, but above this flux density it was not possible to obtain a sinusoidal wave and the losses for such a wave-shape were found by extrapolation on the curve connecting the wattmeter reading and k^2.

TABLE 2A.

Correction for Air Flux for Specimen 4A.

Correction to B for air flux $= 11{\cdot}8H$ (see Table 2).

B (apparent)	H (actual)	H correction on B	B (corrected)
5 000	1·4	20	4 980
10 000	3·5	40	9 960
12 000	6	70	11 930
14 000	10	120	13 880
16 000	23	270	15 730

The method of deducing the corrections to be applied

The total losses obtained have been plotted against the corrected flux densities in Fig. 3, and from these curves the values used in the separation of the losses have been taken. The separation is carried out in Table 3, which also contains the hysteresis losses found by ballistic tests on specimen 4B and the exponents calculated between each pair of successive values of B both for hysteresis and eddy-current losses.

In Table 4 the results are given of a similar analysis of the measurements made by alternating current and ballistically on the remaining specimens detailed in Table 1. In certain cases, however, only two or three ballistic tests were carried out and determinations of the exponent for the same ranges of B as in the a.c. tests could not be made.

Discussion of results of preliminary general investigation.—These results appear to show definitely that above $B = 10\,000$ the exponent of B for hysteresis loss rises much above the Steinmetz value, 1·6, which applies below $B = 10\,000$. In several cases the exponent for

the range $B = 12\,500$ to $15\,000$ approximates to or even exceeds $2\cdot5$, and it would seem likely that, for smaller ranges of B near $15\,000$, values as high as $3\cdot0$ might be obtained. Such values were actually obtained for the range $B = 12\,500$ to $15\,000$ for material which was

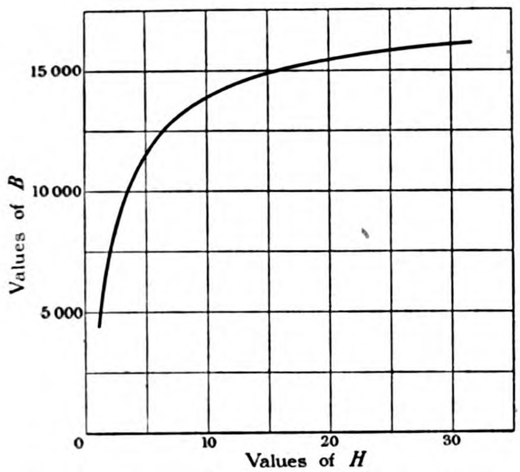

FIG. 2.—Permeability curve on specimen No. 4.

known to be defective. It will be seen that in all cases a fairly close agreement is obtained between the a.c. and ballistic tests. The increase in the exponent is less than the average for lohys, and slightly greater for special lohys specimens, but the number of specimens tested was too few to establish the existence of so small a difference.

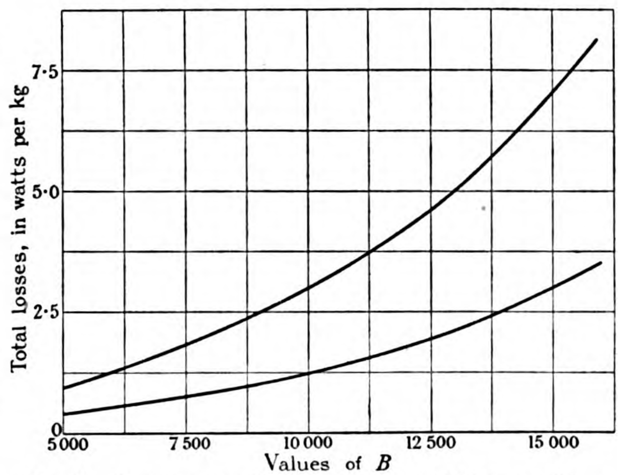

FIG. 3.—Curves connecting total losses and B for specimen No. 4.

The methods adopted in this preliminary general investigation were directed rather to obtaining comparative results on a number of specimens readily

TABLE 3.

Separation of Losses for Specimen 4A.

B	W_1 (at 25 ~)	W_2 (at 50 ~)	H_2 (= $4W_1 - W_2$)	E_2 (= $W_2 - H_2$)	H_2 (from ballistic tests)	Exponents		
						Hysteresis		Eddy-current
						A.C.	Ballistic	
5 000	0·38	0·91	0·61	0·30	0·62	1·68	1·73	1·8
10 000	1·24	3·00	1·96	1·04	2·06	2·11	2·05	1·58
12 500	1·94	4·62	3·14	1·48	3·26	2·53	2·19	1·87
15 000	3·01	7·06	4·98	2·08	4·86			

quite definite in the ballistic results, though less marked owing to the hysteresis loss at flux densities near 10 000 (the region of maximum permeability) being increased much more than at higher flux densities by the greater effect of cutting on the narrow rings used in the ballistic tests. That this is the correct explanation of the lower exponents obtained in the ballistic tests was proved by a complete series of tests carried out on annealed rings and strips (see Appendix II) for which close agreement between the two methods of test was obtained.

The results for the four kinds of sheet material tested do not show any pronounced differences in the manner of variation of the hysteresis loss with B, the exponent increasing to approximately the same extent with B for each material. The increase appears to be slightly than to securing high absolute accuracy in any individual test. Thus the method of separating the total losses into hysteresis and eddy-current components assumes independence of frequency for the hysteresis loss per period, which, although a fairly close approximation, probably introduces some slight error into the a.c. values of hysteresis. At high flux densities, in particular, the results are liable to considerably increased errors, since the corrections to be applied for air flux and for form factor of E.M.F. wave become very large.

In view of the very large increase already observed in the exponent at high flux densities, it becomes of interest to examine the effect of testing at still higher flux densities, since, as no further increase of hysteresis is to be expected when saturation is reached, it would

TABLE 4.

No.	B_{max}	Hysteresis loss in watts/kg at 50 ~ — From a.c. tests	Hysteresis loss in watts/kg at 50 ~ — From ballistic tests	Exponent of B for hysteresis loss — From a.c. tests	Exponent of B for hysteresis loss — From ballistic tests
1*	5 000	0·70	0·60	1·72	1·79
	10 000	2·30	2·07	1·25	
	12 500	3·04			
2	5 000	0·61	0·59	1·62	1·65
	10 000	1·87	1·85	2·09	1·95
	12 500	2·98	2·86	2·29	2·06
	15 000	4·52	4·21		
3	5 000	0·64		1·61	
	10 000	1·96	1·87	1·94	
	12 500	3·02		2·62	
	15 000	4·87			
4	5 000	0·61	0·62	1·68	1·73
	10 000	1·96	2·06	2·11	2·06
	12 500	3·14	3·26	2·53	2·19
	15 000	4·98	4·86		
5	5 000	0·62	0·64	1·57	1·67
	10 000	1·84	2·04	1·75	2·00
	12 500	2·72	3·18	2·86	2·18
	15 000	4·58	4·73		
6	5 000	0·62		1·61	
	10 000	1·91	2·12	2·10	
	12 500	3·05		2·84	
	15 000	5·00			
7	5 000	0·42	0·42	1·66	1·67
	10 000	1·33	1·34	1·79	1·86
	12 500	1·98	2·03	2·41	2·26
	15 000	3·07	3·06		
8	5 000	0·39		1·74	
	10 000	1·30	1·54	2·24	
	12 500	2·14		2·51	
	15 000	3·38			
9	5 000	0·41		1·64	
	10 000	1·28	1·38	2·03	
	12 500	2·01		2·38	
	15 000	3·10			
10	5 000	0·36	0·43	1·70	1·65
	10 000	1·18	1·37	1·93	1·82
	12 500	1·81	2·05	2·70	2·26
	15 000	2·97	3·09		
11	5 000	0·67	0·68	1·58	1·66
	10 000	2·00	2·15	1·90	1·88
	12 500	3·08	3·27	2·48	2·26
	15 000	4·84	4·93		
12	5 000	0·62	0·69	1·61	1·61
	10 000	1·90	2·11	1·83	1·78
	12 500	2·86	3·14	2·64	2·31
	15 000	4·63	4·78		
13	5 000	0·62		1·62	
	10 000	1·90	2·18	1·97	
	12 500	2·95		2·57	
	15 000	4·71			
14	5 000	0·60	0·67	1·58	1·61
	10 000	1·79	2·05	1·97	
	12 500	2·78		2·91	
	15 000	4·72			

* Owing to the thickness of the laminations of this sample, the eddy-current loss was very large and the temperature-rise so rapid at high inductions that reliable results could not be obtained. This also accounts for the apparently low value of hysteresis at $B = 12\,500$.

seem that the ratio of variation must at some point begin to diminish with increased B.

It was therefore decided to make a more accurate and detailed examination of the variation of losses on certain representative specimens, and to carry this examination to higher values of B.

(4) MORE DETAILED EXAMINATION OF CERTAIN SPECIMENS.

Construction of new square.—To allow of tests being made at higher flux densities a new Lloyd square was constructed in which, using the same general disposition and numbers of turns in the windings, the following improvements were introduced :—

(1) Cross-section of secondary coil was reduced from approx. 20 cm² on the old square to 8·5 cm², thereby reducing the air-flux correction to 40 per cent of its previous value. This is very important for tests at high flux densities.

(2) Resistance of primary winding was greatly reduced by winding with very much thicker wire. This reduces the distortion of the E.M.F. wave and hence the correction to be applied for departure of form factor from a sine-wave value. It is also of importance in diminishing the I^2R heating due to the magnetizing current, which is liable to become considerable at high flux densities and to affect the temperature of the specimen.

Method of testing and working out results.—Using this square, a further complete series of tests was made on specimens Nos. 3, 6, 8, 12, i.e. one each of lohys, special lohys, high-resistance and medium-resistance material.

As in the first part of the investigation, parallel tests were made throughout by the a.c. and the ballistic methods. The a.c. tests were carried out as before at frequencies of 25 and 50 periods per second and at a number of flux densities from 10 000 to the highest value that could be reached without excessive heating. Owing to the improved characteristics of the new square, it was possible to obtain satisfactory results for flux densities up to about 18 000 on the softer materials and 17 000 on the high-resistance material.

At the highest values of B attained, the I^2R heating, even with the new square, was sufficient to produce an appreciable rise of temperature in the time required to make the adjustments and take the readings. To minimize the effect of this, the temperature of the samples was read by a thermo-junction and the square was allowed to cool between successive readings so that the temperature when the readings were taken did not vary more than 1° or 2°.

The separation of the losses was carried out independently at each frequency from the curve connecting the power loss and the square of the form factor. This avoids the assumption that the hysteresis loss per period is independent of the frequency, but assumes that it is independent of form factor. From the fundamental formula

$$W = \eta f B^x + \xi f^2 k^2 B^y$$

it follows that if f and B are kept constant

$$W = A + Bk^2$$

i.e., the curve connecting W and k^2 should be a straight line.

In carrying out the tests a series of readings at different form factors was taken at each value of B by inserting various series resistances in the magnetizing circuit, and curves connecting W/f and fk^2 were drawn. (These curves are identical with curves connecting W and k^2, except for a change of scale for any series of tests at a given B and frequency, but they allow a direct comparison to be made between the eddy-current coefficients found from the 25- and 50-period tests.) These curves were found to approximate very accurately to straight lines, suggesting that the assumption of independence of form factor for the hysteresis loss is at least a close approximation to the facts. The slope of each of these curves was then found and must evidently be equal to ξB^y. Plotting the slopes logarithmically against the corresponding values of B, a curve is obtained the slope of which is the exponent of B for the eddy-current

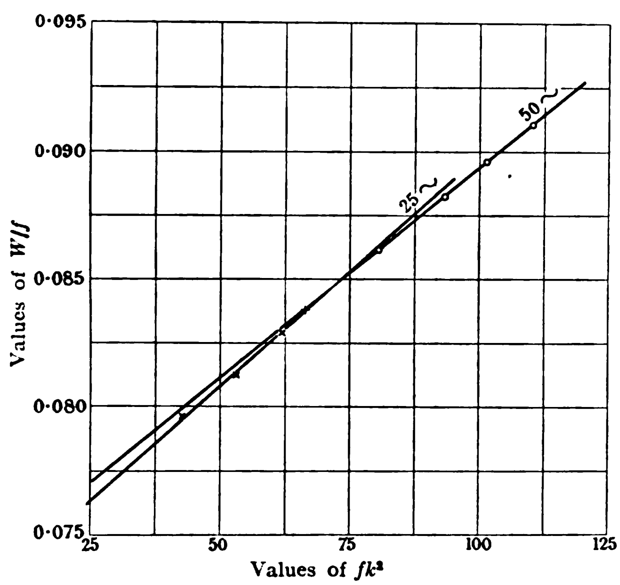

FIG. 4.—Curves connecting W/f and fk^2 for specimen No. 8A (high-resistance material) at $B = 16\,000$.

loss. In order to eliminate the errors of individual tests the separation of the losses was carried out by deducing the eddy-current loss for a sine-wave form for each value of B from the curve and then calculating the hysteresis loss by subtracting this value from the total loss for a sine-wave form, determined, as previously described, by extrapolation on the curve connecting W/f and fk^2.

The ballistic tests were carried out exactly as before, except that the tests were made on the same strips as were used for the a.c. tests while still built up in the Lloyd square instead of on separate ring specimens. The square was then treated as a ring, the magnetizing force being calculated from the primary current, and the flux density being measured by using one of the secondary windings as a search coil. This eliminates any discrepancy due to different effects of cutting, but may lead to some inaccuracy in the measurement of H owing to the magnetic circuit not being perfectly uniform. Comparative tests, however, showed that the error due to this was quite small (see Appendix 3).

Comparable values of hysteresis loss measured ballistically and by alternating current at 25 and 50 periods per second were thus obtained entirely independently and afforded a double check on the variation of loss with B.

Results obtained.—As in the first part of the investigation the complete a.c. results, for one sample No. 8A, are given in Table 5, the calculation of the air-flux correction to the apparent value of $B_{max.}$ being shown in Table 5A.

Curves connecting W/f and fk^2 were drawn from these results for each value of $B_{max.}$ at which tests were made, those for $B_{max.} = 16\,000$ being shown in Fig. 4. The slope of each of these curves was measured and is recorded in Table 6. The logarithms of the slopes are plotted against log B for both frequencies in Fig. 5, and it will be seen that the points for each frequency lie very nearly on a straight line the slope of which is slightly

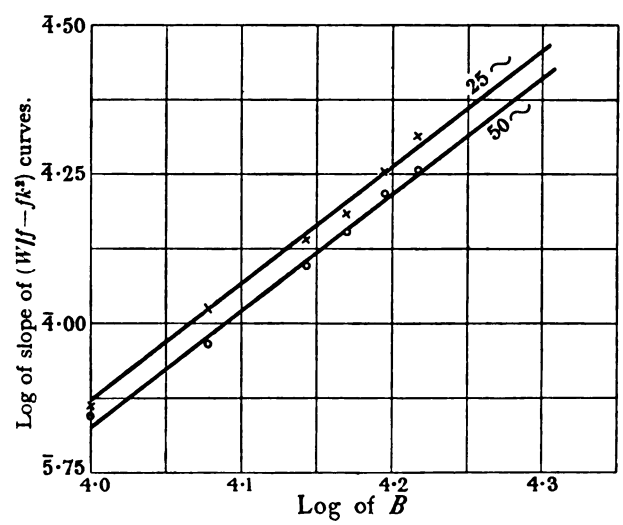

FIG. 5.—Logarithmic curves connecting slope of $(W/f\text{–}fk^2)$ curves with B for specimen No. 8A (high-resistance material).

less than 2, indicating a practically constant index of B of slightly less than 2. The curve for 50 periods per second, however, falls appreciably below that for 25 periods per second, indicating a lower value of the eddy-current coefficient, ξ, at the higher frequency.

Values of the slope corresponding to each value of B have been taken from these curves and are recorded in Table 6. The eddy-current loss for any given form factor may then be found by multiplying the value of the slope by the appropriate value of f^2k^2. For a sine wave $k^2 = 1 \cdot 232$, hence the values of W_E/f for a sine-wave form given in the table are obtained by multiplying the slopes by $1 \cdot 232 f$.

The corresponding values of total loss/frequency ($= W/f$) for a sine-wave form are read off the curves connecting W/f and fk^2 by making $fk^2 = 1 \cdot 232 f$.

Subtracting W_E/f from W/f the value of hysteresis loss/f ($= W_H/f$) is found, and hence the hysteresis loss may be obtained. Values of hysteresis

TABLE 5.

A.C. Results on Specimen 8A (*high-resistance material*).

Mass $m_1 = 1\,108$ grammes. Section of specimen, $A = 1\cdot465$ cm². Mass of corners, $m_2 = 62$ grammes. Overlap at corners $= 4\cdot3$ mm. Effective mass, $m = 1\,113$ grammes. Magnetizing turns, $N_1 = 640$. Secondary turns (wattmeter), $N_2 = 160$.
Cross-section of secondary coil $= 8\cdot5$ cm², therefore correction for air flux $= [(8\cdot5 - 1\cdot465)/1\cdot465]H = 4\cdot8H$.

$B_{max.}$ (apparent)	V_{mean}	$V_{R.M.S.}$	k	fk^2	Total watts (corrected)	$\frac{\text{Watts}}{\text{kg}} = W$	$\frac{W}{f}$	$B_{max.}$ (corrected)
(1) *Frequency* $f = 25$ *periods per sec. Secondary turns* (*voltmeter*), $N_3 = 40$.								
10 000	0·586	0·658	1·124	31·6	0·765	0·687	0·02748	9 990
		0·726	1·239	38·4	0·780	0·701	0·02804	
		0·806	1·375	47·3	0·798	0·717	0·02868	
		0·844	1·440	51·8	0·804	0·722	0·02888	
						Sine wave	0·02743	
12 000	0·703	0·795	1·131	32·0	1·113	1·000	0·040	11 970
		0·846	1·204	36·3	1·129	1·014	0·04064	
		0·950	1·351	45·6	1·154	1·036	0·04144	
		1·065	1·515	57·4	1·187	1·067	0·04268	
						Sine wave	0·0398	
14 000	0·820	0·96	1·17	34·2	1·592	1·430	0·0572	13 900
		1·07	1·305	42·6	1·625	1·460	0·0584	
		1·198	1·46	53·3	1·667	1·498	0·05992	
		1·355	1·652	68·3	1·723	1·547	0·06188	
						Sine wave	0·0567	
15 000	0·879	1·093	1·243	38·6	1·936	1·739	0·06956	14 790
		1·218	1·385	48·0	1·979	1·776	0·07104	
		1·245	1·416	50·2	1·986	1·784	0·07136	
		1·435	1·632	66·6	2·054	1·845	0·07380	
						Sine wave	0·0684	
16 000	0·938	1·23	1·311	42·9	2·213	1·990	0·0796	15 650
		1·368	1·459	53·2	2·261	2·031	0·08124	
		1·478	1·575	62·0	2·308	2·072	0·08288	
		1·53	1·63	66·5	2·331	2·095	0·0838	
						Sine wave	0·0774	
17 000	0·996	1·378	1·383	47·8	2·431	2·184	0·08736	16 480
		1·463	1·469	54·0	2·467	2·214	0·08856	
		1·50	1·506	56·7	2·490	2·237	0·08948	
		1·575	1·582	62·6	2·522	2·267	0·09068	
						Sine wave	0·0838	
(2) *Frequency* $f = 50$ *periods per sec. Secondary turns* (*voltmeter*), $N_3 = 20$.								
10 000	0·586	0·663	1·131	64·0	1·662	1·493	0·02986	9 990
		0·690	1·177	69·3	1·681	1·511	0·03022	
		0·746	1·274	81·2	1·727	1·552	0·03104	
		0·801	1·367	93·5	1·776	1·596	0·03192	
						Sine wave	0·0297	
12 000	0·703	0·803	1·142	65·3	2·436	2·187	0·04374	11 970
		0·860	1·223	74·8	2·480	2·228	0·04456	
		0·973	1·384	95·8	2·590	2·326	0·04652	
		1·063	1·511	114·2	2·680	2·407	0·04814	
						Sine wave	0·0433	
14 000	0·820	0·961	1·171	68·6	3·487	3·131	0·06262	13 900
		1·128	1·375	94·5	3·660	3·289	0·06578	
		1·24	1·511	114·2	3·809	3·421	0·06842	
		1·353	1·650	136·1	3·954	3·552	0·07104	
						Sine wave	0·0617	
15 000	0·879	1·078	1·226	75·2	4·225	3·795	0·0759	14 790
		1·198	1·362	92·8	4·366	3·921	0·07842	
		1·298	1·476	109·0	4·488	4·031	0·08062	
		1·39	1·581	125·0	4·605	4·137	0·08274	
						Sine wave	0·0739	
16 000	0·938	1·19	1·269	80·5	4·798	4·309	0·08618	15 650
		1·283	1·367	93·4	4·912	4·412	0·08824	
		1·335	1·424	101·4	4·991	4·484	0·08968	
		1·395	1·487	110·5	5·065	4·552	0·09104	
						Sine wave	0·0830	
17 000	0·996	1·328	1·334	89·0	5·27	4·73	0·0946	16 480
		1·388	1·394	97·2	5·35	4·81	0·0962	
		1·495	1·501	112·7	5·50	4·94	0·0988	
		1·578	1·584	125·5	5·65	5·08	0·1016	
						Sine wave	0·0897	

loss and total loss in watts per kg are given in Table 6 for each value of B at which tests were made, and for 25 and 50 periods per second. They are also plotted in Fig. 6, and from these curves the final values were read. The results are shown in Table 7, where the hysteresis loss at both frequencies has been expressed in watts per kg at 50 periods per second, and where the ballistic values determined from the areas of the static loops, also expressed in watts per kg at 50 periods per second, are given for comparison. The exponent of B for the hysteresis loss is also given for each set of results for various ranges of B. Results corresponding to those in Tables 6 and 7 are given for specimens No. 3A (lohys), No. 6A (special lohys) and No. 12A (medium resistance) respectively in Tables 8 and 9, 10 and 11, and 12 and 13.

TABLE 5A.

Correction for Air Flux for Specimen 8A. (*high-resistance material*).

Correction on $B_{max.}$ for air flux = $4 \cdot 8H$ (see Table 5).

B (apparent)	H (actual)	H correction on B	B (corrected)
10 000	3	10	9 990
12 000	6	30	11 970
14 000	21	100	13 900
15 000	43	210	14 790
16 000	73	350	15 650
17 000	108	520	16 480

Discussion of results and conclusions.—The results obtained in the more thorough examination of the four representative specimens fully confirm the conclusions drawn from the preliminary general investigation and justify the suggestion made in connection with it that the exponent for limited ranges of B may reach values of $3 \cdot 0$ or more. In the case of specimen No. 12A the ratio between B = 15 000 and B = 16 000 even exceeds $4 \cdot 0$. It will be seen that the three sets of values of hysteresis loss, which have been obtained entirely independently, give exponents which are in very good agreement, the discrepancies between the three sets being apparently due only to incidental errors of measurement and not greater than are to be expected when deriving the exponent for such small ranges of B. Thus, although there are differences between the values of hysteresis loss obtained at different frequencies, probably

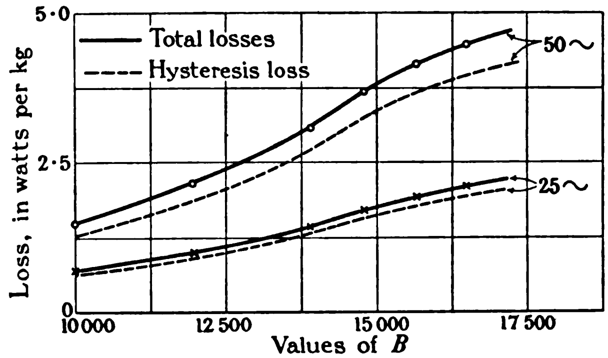

FIG. 6.—Curves connecting losses and B for specimen No. 8A (high-resistance material).

TABLE 6.

Separation of Losses for Specimen No. 8A (*high resistance*).

B	Slope of $\frac{W}{f} - fk^2$ curve × 10^4 — Measured	Slope of $\frac{W}{f} - fk^2$ curve × 10^4 — From log curve	$\frac{W_E}{f}$ (sine wave)	$\frac{W}{f}$ (sine wave)	$\frac{W_H}{}$	W_H	W (sine wave)
			Frequency f = 25 periods per sec.				
9 990	0·73	0·75	0·00231	0·02743	0·0251	0·63	0·69
11 970	1·06	1·06	0·0033	0·0398	0·0365	0·91	1·00
13 900	1·38	1·41	0·0043	0·0567	0·0524	1·31	1·42
14 790	1·53	1·59	0·0049	0·0684	0·0635	1·59	1·71
15 650	1·79	1·78	0·0055	0·0774	0·0719	1·80	1·94
16 480	2·11	1·97	0·0061	0·0838	0·0777	1·94	2·10
			Frequency f = 50 periods per sec.				
9 990	0·70	0·67	0·0042	0·0297	0·0255	1·28	1·49
11 970	0·92	0·95	0·0059	0·0433	0·0374	1·87	2·17
13 900	1·25	1·27	0·0078	0·0617	0·0539	2·70	3·09
14 790	1·42	1·43	0·0088	0·0739	0·0651	3·26	3·70
15 650	1·65	1·61	0·0099	0·0830	0·0731	3·66	4·15
16 480	1·81	1·77	0·0109	0·0897	0·0788	3·94	4·49

due to non-homogeneity of the material, it seems certain that the exponents represent fairly accurately the true values for the material. The results thus indicate a very rapid increase of the exponent in the neighbourhood of $B = 15\,000$, followed, as was anticipated, by a rapid decrease to quite low values above $B = 17\,000$. Too much reliance should not be placed on the figures for $B = 18\,000$, but since fairly close agreement was obtained between ballistic and a.c. results it may be assumed that the general shape of the curve, at any rate, follows the course indicated.

So far as the hysteresis loss up to $B = 16\,000$ is concerned, therefore, the results obtained appear to confirm those placed in the third group of the summary at the end of Section 2 as indicating ratios of variation considerably above 2·0, and although giving somewhat higher values they are not inconsistent with those in the second group which showed exponents of about 2. With the results in the first group confirming Steinmetz's law up to very high flux densities, however, the observations recorded in the paper appear to be in direct conflict. The most important of these are Nicholson's, which were obtained, as described above, by employing an altogether different method of allowing for distortion of the E.M.F. wave. This renders impossible a detailed examination of the points of difference between the two sets of observations, and there seems no obvious explanation of the discrepancy between them.

The significance of the departure from Steinmetz's law observed may be appreciated by calculating the loss at $B = 16\,000$ from that at $B = 10\,000$, assuming a constant exponent. The observed values at $B = 16\,000$ will be found to be 40–50 per cent higher than those calculated.

The rapid fall of the exponent at higher flux densities, although, as suggested, theoretically probable, does not seem to have been generally observed, and, as mentioned previously, the results of Baily, obtained by the calorimetric method and showing a similar effect, are of considerable interest in this connection. He found the decrease in the exponent to begin at about $B = 18\,000$. This is a rather higher value than that at which it was observed in this investigation, but it must be remembered that Baily's experiments were made about 1895 and, consequently, were carried out on soft-iron sheets instead of on the alloy materials now used, for which the saturation flux density is appreciably lower.

One effect of this successive increase and decrease in the exponent is that, where the losses are determined under such conditions that the flux density varies considerably in different parts of the circuit as in an actual machine, the exponent of B for hysteresis loss will appear to be much more constant than it really is. This will apply to such results as those recently discussed by E. Hughes.*

The curves in Figs. 4 and 5, and the results given in Tables 8, 10 and 12, show that the slope of the $W/f - fk^2$ curves is slightly less at 50 periods than at 25 periods, corresponding to a slightly lower value of the eddy-current coefficient. This holds fairly consistently for all specimens and at all values of B. It is quite a small effect and, like the apparent variation of hysteresis with frequency, is believed to be due to non-homogeneity of the material due to the presence of slight scale.

TABLE 7.

Comparison of Results on Specimen No. 8A (high resistance).

B	Total loss in $\frac{\text{watts}}{\text{kg}}$		Hysteresis loss in $\frac{\text{watts}}{\text{kg}}$ At 50 ~ per sec.			Exponent of B for hysteresis loss		
	At 25 ~	At 50 ~	From 25 ~ results	From 50 ~ results	From static loops	25 ~	50 ~	Static
10 000	0·69	1·49	1·26	1·28	1·26			
						2·02	2·08	1·81
12 000	1·00	2·18	1·82	1·87	1·75			
						2·51	2·52	2·58
14 000	1·45	3·14	2·68	2·76	2·61			
						3·0	2·93	2·73
15 000	1·78	3·83	3·30	3·38	3·15			
						1·93	1·77	2·14
16 000	2·01	4·30	3·72	3·79	3·62			
						1·45	1·27	0·93
17 000	2·19	4·65	4·06	4·09	3·83			

The slopes of the logarithmic curves plotted from the results in Tables 6, 8, 10 and 12, of which Fig. 5 is an example, show that the eddy-current exponent is nearly constant for each specimen and is in general rather less than 2. This tendency at high flux densities has been noted by several previous observers.

To summarize the conclusions deduced from the results recorded, it has been shown that:—

(1) In all the principal types of commercial sheet material in use at the present time, the rate of increase of the hysteresis loss with B is considerably greater at flux densities above $B = 10\,000$ than is indicated by Steinmetz's law or than appears to have been generally realized. In most specimens over a small range in the neighbourhood of $B = 15\,000$ the variation is as rapid as the 2·5th power of B, and in some cases it exceeds the 3rd or even the 4th power of B.

(2) Above about $B = 16\,000$ the rate of increase falls

* See Appendix IV, (23).

off very rapidly and drops again to the 1·6th power or even lower.

(3) The eddy-current index at high flux densities is fairly constant and generally rather less than 2.

(4) The apparent values of hysteresis and eddy-current losses in ordinary commercial sheet material depend to a considerable extent on frequency. Experiments not recorded in the paper indicate that this is due to non-homogeneity of the sheet. These effects do not appreciably alter the exponents observed.

In conclusion the author wishes to express his thanks to Messrs. J. Lysaght, Ltd., for kindly supplying the samples of sheet material used in the investigation; to Mr. D. W. Dye, B.Sc., for his help and advice throughout the course of the work; and to Mr. L. H. Ford, B.Sc., for his assistance in carrying out the experiments described.

APPENDIX 1.

Comparison of Permeabilities Measured Ballistically and by Alternating Current.

Several tests were made in the course of the investigation to compare the values of permeability obtained by a.c. measurements with those given by the ballistic method.

For the a.c. tests the primary of a mutual inductance of 0·01 henry wound on a marble bobbin was connected

TABLE 8.

Separation of Losses for Specimen No. 3A (*lohys*).

B	Slope of $\frac{W}{f} - fk^2$ curve $\times 10^4$		$\frac{W_E}{f}$ (sine wave)	$\frac{W}{f}$ (sine wave)	$\frac{W_H}{f}$	W_H	W (sine wave)
	Measured	From log curve					
			Frequency f = 25 periods per sec.				
9 990	4·02	3·98	0·0123	0·0490	0·0367	0·92	1·23
11 980	5·76	5·32	0·0164	0·0685	0·0521	1·30	1·71
13 970	6·63	6·84	0·0211	0·0966	0·0755	1·89	2·42
14 960	7·41	7·62	0·0235	0·1146	0·0911	2·28	2·87
15 920	8·14	8·42	0·0259	0·1345	0·1086	2·72	3·36
16 820	9·43	9·21	0·0284	0·1496	0·1212	3·03	3·74
17 700	10·22	10·0	0·0308	0·1618	0·1310	3·28	4·05
			Frequency f = 50 periods per sec.				
9 990	3·64	3·62	0·0223	0·0613	0·0390	1·95	3·07
11 980	5·59	4·88	0·0301	0·0857	0·0556	2·78	4·29
13 970	6·17	6·28	0·0387	0·1194	0·0807	4·04	5·97
14 960	6·61	7·05	0·0434	0·1397	0·0963	4·82	6·99
15 920	8·02	7·82	0·0482	0·1616	0·1134	5·67	8·08
16 820	8·52	8·57	0·0528	0·1816	0·1288	6·44	9·08
17 700	9·19	9·32	0·0574	0·1947	0·1373	6·87	9·74

TABLE 9.

Comparison of Results on Specimen No. 3A (*lohys*).

B	Total loss in $\frac{\text{watts}}{\text{kg}}$		Hysteresis loss in $\frac{\text{watts}}{\text{kg}}$ at 50 ~ per sec.			Exponent of B for hysteresis loss		
	At 25 ~	At 50 ~	From 25 ~ results	From 50 ~ results	From static loops	25 ~	50 ~	Static
10 000	1·23	3·08	1·84	1·95	1·73	1·90	1·96	2·00
12 000	1·72	4·31	2·60	2·79	2·49	2·46	2·43	2·30
14 000	2·44	6·01	3·80	4·06	3·55	2·82	2·60	2·57
15 000	2·90	7·04	4·62	4·86	4·24	2·64	2·61	2·73
16 000	3·39	8·19	5·48	5·75	5·06	2·0	2·14	1·92
17 000	3·81	9·24	6·18	6·54	5·68	1·47	1·19	1·78
18 000	4·15	9·94	6·72	7·00	6·29			

in series with the magnetizing winding of the square. Then after adjusting to any desired $B_{max.}$ by means of the V_{mean} reading in the usual way, the moving-coil galvanometer (G) was connected through the synchronous commutator to the secondary of the mutual inductance, the commutator was again adjusted to give the maximum reading and the value of V_{mean} indicated was noted.

Then $$V'_{mean} = 4fMI_{max.}$$

where M = mutual inductance, in henrys,
$I_{max.}$ = maximum value of magnetizing current, in amperes,
f = frequency, in periods per second,
V'_{mean} = reading of moving-coil galvanometer, in volts.

From this expression the maximum value of the magnetizing current in the square may be at once deduced and, treating the square as a ring in the way described in the paper, a simple calculation gives the value of $H_{max.}$ corresponding to the $B_{max.}$ at which the reading was taken.

Table 14 gives a few typical results obtained on specimen No. 3 with the ballistic values for comparison.

These results indicate clearly that at ordinary commercial frequencies the permeability ($B_{max.}/H_{max.}$) measured by alternating current is practically identical with that found ballistically. A considerable number of similar tests were made with the same results.

It seemed worth while to record these results, since N. W. McLachlan * in a paper on "The Magnetic

* See Appendix IV, (24).

TABLE 10.

Separation of Losses for Specimen No. 6A (special lohys).

B	Slope of $\frac{W}{f} - fk^2$ curve × 10^4		$\frac{W_E}{f}$ (sine wave)	$\frac{W}{f}$ (sine wave)	$\frac{W_H}{f}$	W_H	W (sine wave)
	Measured	From log curve					
Frequency f = 25 periods per sec.							
9 990	2·81	2·73	0·0084	0·0453	0·0369	0·92	1·13
11 980	3·65	3·67	0·0113	0·0636	0·0523	1·31	1·59
13 950	4·58	4·74	0·0146	0·0906	0·0760	1·90	2·27
14 930	5·12	5·34	0·0165	0·1135	0·0970	2·43	2·84
15 880	5·98	5·93	0·0183	0·1395	0·1212	3·03	3·49
16 770	6·45	6·48	0·0200	0·1575	0·1375	3·44	3·94
17 630	7·02	7·03	0·0217	0·1713	0·1496	3·74	4·28
Frequency f = 50 periods per sec.							
9 990	2·57	2·64	0·0163	0·0533	0·0370	1·85	2·67
11 980	3·55	3·68	0·0227	0·0746	0·0519	2·60	3·73
13 950	4·79	4·65	0·0286	0·1059	0·0773	3·87	5·30
14 930	5·19	5·21	0·0321	0·1322	0·1001	5·01	6·61
15 880	5·91	5·81	0·0358	0·1587	0·1229	6·15	7·94
16 770	6·29	6·36	0·0392	0·180	0·1408	7·04	9·0
17 630	7·39	6·92	0·0426	0·1931	0·1505	7·53	9·66

TABLE 11.

Comparison of Results on Specimen No. 6A (special lohys).

B	Total losses in $\frac{\text{watts}}{\text{kg}}$		Hysteresis loss in $\frac{\text{watts}}{\text{kg}}$ At 50 ∼ per sec.			Exponent of B for hysteresis loss		
	At 25 ∼	At 50 ∼	From 25 ∼ results	From 50 ∼ results	From static loops	25 ∼	50 ∼	Static
10 000	1·13	2·67	1·84	1·85	1·77			
						1·94	1·89	1·83
12 000	1·59	3·74	2·62	2·61	2·47			
						2·48	2·65	2·42
14 000	2·30	5·36	3·84	3·93	3·59			
						3·70	3·77	3·90
15 000	2·89	6·71	4·96	5·10	4·70			
						3·15	3·21	3·50
16 000	3·55	8·09	6·18	6·28	5·89			
						2·23	2·25	2·27
17 000	4·03	9·22	7·06	7·19	6·75			
						1·38	1·10	1·52
18 000	4·39	9·83	7·64	7·66	7·36			

TABLE 12.

Separation of Losses for Specimen No. 12A *(medium resistance).*

B	Slope of $\frac{W}{f} - fk^2$ curve × 10^4		$\frac{W_E}{f}$ (sine wave)	$\frac{W}{f}$ (sine wave)	$\frac{W_H}{f}$	W_H	W (sine wave)
	Measured	From log curve					
	Frequency f = 25 periods per second.						
9 990	1·58	1·57	0·0048	0·0417	0·0369	0·92	1·04
11 980	2·20	2·16	0·0067	0·0579	0·0512	1·28	1·45
13 950	2·76	2·81	0·0087	0·0805	0·0718	1·80	2·01
14 910	3·15	3·16	0·0097	0·0969	0·0872	2·18	2·42
15 840	3·35	3·52	0·0108	0·1230	0·1122	2·81	3·08
16 730	3·87	3·86	0·0119	0·1468	0·1349	3·37	3·67
17 580	3·94	4·23	0·0130	0·1663	0·1533	3·83	4·16
	Frequency f = 50 periods per second.						
9 990	1·44	1·42	0·0088	0·0462	0·0374	1·87	2·31
11 980	1·92	2·00	0·0123	0·0640	0·0517	2·59	3·20
13 950	2·69	2·67	0·0164	0·0889	0·0725	3·63	4·45
14 910	3·05	3·06	0·0188	0·1067	0·0879	4·40	5·34
15 840	3·48	3·39	0·0209	0·1341	0·1132	5·66	6·71
16 730	3·94	3·77	0·0232	0·1608	0·1376	6·88	8·04
17 580	3·84	4·15	0·0256	0·1817	0·1561	7·81	9·09

TABLE 13.

Comparison of Results on Specimen No. 12A *(medium resistance).*

B	Total losses in $\frac{\text{watts}}{\text{kg}}$		Hysteresis loss in $\frac{\text{watts}}{\text{kg}}$ at 50 periods per sec.			Exponent of B for hysteresis loss		
	At 25 ~	At 50 ~	From 25 ~ results	From 50 ~ results	From static loops	25 ~	50 ~	Static
10 000	1·04	2·31	1·84	1·88	1·79	1·81	1·78	1·75
12 000	1·46	3·22	2·56	2·60	2·46	2·24	2·25	2·27
14 000	2·05	4·49	3·62	3·68	3·49	3·08	2·94	3·11
15 000	2·48	5·44	4·48	4·51	4·33	4·05	4·13	4·25
16 000	3·20	6·97	5·82	5·89	5·70	3·23	3·32	3·33
17 000	3·84	8·40	7·06	7·19	6·96	2·32	2·31	2·18
18 000	4·38	9·51	8·06	8·20	7·88			

TABLE 14.

(M = 0·01 *henry. Frequency* f = 50 *periods per sec.*)

$B_{max.}$ (apparent)	$B_{max.}$ (corrected)	V'_{mean}	$I_{max.}$	$H_{max.}$	H (ballistic)
10 000	9 990	0·68	0·34	2·74	2·64
12 000	11 980	1·05	0·53	4·27	4·16
14 000	13 970	1·82	0·91	7·32	7·20
15 000	14 960	2·88	1·44	11·6	11·5
16 000	15 920	5·61	2·81	22·6	22·8
17 000	16 820	12·41	6·21	50·0	49·8

Behaviour of Iron under Alternating Magnetization of Sinusoidal Wave-form" published results showing higher values of B, for given values of H, in a.c. than in d.c. (ballistic) tests.

This result, of which no theoretical explanation was suggested and which on theoretical grounds seems highly improbable, was obtained by making use of a much less direct method of measuring the a.c. permeabilities than that described above, involving the use of an oscillograph taking an appreciable current. His results also showed a marked change in the value of $B_{max.}$ for a given $H_{max.}$ when a small change in the wave-shape of the magnetizing current was made

(form factor of current-wave altered from 1·11 to 1·19), the frequency remaining the same.

This suggests that the effect observed is not due to a genuine difference between the d.c. and a.c. permeabilities, and the author thinks that the more direct measurements recorded above represent with much greater accuracy the true relation between the properties of iron sheet under direct and alternating magnetization.

APPENDIX 2.

Tests on Annealed Strips and Rings (to Eliminate the Effects of Cutting).

In order to determine the magnitude of the effect of cutting and to obtain satisfactorily comparable results, both ballistically and by alternating current on strips and rings, several complete series of tests were made at flux densities from 10 000 to 18 000 on the medium-resistance specimens Nos. 12A and 12B both before and after annealing.

The results of a.c. and ballistic tests on specimen No. 12A have already been recorded in Tables 12 and 13, and of ballistic tests on No. 12B in Table 4. A corresponding series of a.c. tests on No. 12B was made at 50 periods per second by the method described in the paper under "Detailed Examination of Certain Specimens."

Both strips and rings were then annealed together and the whole series of tests was repeated on both specimens. The complete set of results, with those obtained before annealing for comparison, is given in Table 15.

The results show clearly that the cause of the previous differences between the rings and strips was the greater effect of cutting on the rings. Annealing produced reductions in the hysteresis loss up to 25 per cent on the rings and up to 10 per cent on the strips, the reductions naturally being greater at $B = 10\,000$ than at higher flux densities. The resulting values for rings and strips will be seen to be nearly identical. The a.c. and ballistic results are also in very fair agreement, the a.c. values, however, as found in the results embodied in the paper, tending to be rather higher than the ballistic values. In the only case in which this rule is broken—the results at high flux densities on rings after annealing—it is to be noted that the a.c. results are not very reliable, as under these conditions the wave-shape is very distorted and a very large correction has to be made for the form factor.

Table 15.

Comparison of Values of Hysteresis Loss in Watts per kg at 50 periods per second obtained on Specimens 12A and 12B before and after Annealing.

B	Before annealing				After annealing			
	Rings		Strips		Rings		Strips	
	A.C.	Ballistic	A.C.	Ballistic	A.C.	Ballistic	A.C.	Ballistic
10 000	2·29	2·11	1·88	1·79	1·72	1·63	1·69	1·66
12 000	3·14	2·92	2·60	2·46	2·42	2·29	2·37	—
14 000	4·19	3·95	3·68	3·49	3·47	3·35	3·39	3·28
15 000	—	4·78	4·51	4·33	4·48	4·40	4·28	4·19
16 000	6·27	6·04	5·89	5·70	5·78	5·54	5·73	5·56
17 000	—	—	7·19	6·96	6·61	6·56	6·85	—
18 000	8·63	—	8·20	7·88	7·26	7·37	7·51	7·42

APPENDIX 3.

Accuracy of Ballistic Tests on Square.

To check the accuracy of results obtained by treating the strips built up with corners in the Lloyd square as a ring for the purpose of making ballistic measurements, permeability curves on specimen No. 3A (lohys) were taken ballistically :—

(1) Treating the specimen as a ring as described in the paper.

(2) Measuring *H* by flat search-coils placed on either side of the strips near the middle of the magnetizing coils, and measuring *B* by search-coils wound on the same length of specimen as was covered by the *H* coils.

The results obtained are given in Table 16.

Table 16.

H	*B* [Method (1)]	*B* [Method (2)]
2·5	9 670	9 850
5·0	12 580	12 950
7·5	13 930	14 110
10·0	14 580	14 700
15·0	15 210	15 270
25·0	15 800	15 830
50·0	16 710	16 710

It will be seen that the discrepancy except for fairly low values of H is very small indeed, and that its maximum value is less than 3 per cent.

A further evidence of the accuracy of the method is given by results quoted in Appendix 2 for strips and rings annealed together. The close agreement between the ballistic results on the two sets of annealed samples again indicates that no serious error is involved in treating the square as a ring.

APPENDIX 4.

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Discussion before The Institution, 17 December, 1925

Mr. H. S. Holbrook: It has been known for many years that in actual apparatus the core losses at high flux densities increase much more rapidly than would be expected from the Steinmetz formula but, as far as we know, no one has previously investigated the subject to the same extent as the present author. The paper is very opportune because, as the author mentions in his opening statement, there is a very definite tendency in modern practice to use higher flux densities in cores than has been customary in the past. It is interesting to note that our Continental and American competitors, in transformers at any rate, habitually run their cores at flux densities some 20 per cent higher than the average figures in British designs. This means not only that they are using smaller cores, but that due to the resulting reduction in mean length of turn of the windings they are able to get greater outputs for the same copper losses, or, alternatively, use a smaller tank for the same transformer rating. This is a contributory reason why orders are lost on price to American and Continental firms, and therefore the paper is of national importance. I was rather surprised that the author did not mention in his bibliography the work of Mr. John D. Ball as reported in the discussion before the American Institute of Electrical Engineers on his paper on the "Unsymmetric Hysteresis Loop."* He suggested that, as a result of his experiments, the variation in the Steinmetz exponent which had been noted by various investigators could be explained by the presence of scale on the steel. Mr. Ball stated that the scale tended to have a higher permeability than the steel itself but at the same time it had a greater loss coefficient. The flux distribution between the scale and the steel changes as the flux density is increased, and under such conditions one could not expect the total hysteresis loss to follow any regular law. Has the author considered Mr. Ball's work? In any case, of course, the scale on alloy steels, especially the 4 per cent silicon steel, is one of our most difficult practical problems. The author mentioned that at very high flux densities he found a decrease in the exponent. Some of our own curves show this, but in view of difficulties in making such tests I am afraid that I personally had been inclined to the view that the decrease represented some

* *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 2729.

error in the test-results. The author has obtained remarkable consistency in his experimental results. In Appendix 2 he gives some figures which illustrate the advantage of annealing alloy steels. The specimens on which he gives the results were of medium-resistance quality. Has he any figures in connection with the high-resistance steels? It is the present general practice in purchasing specifications and descriptive matter to compare electrical sheet steels on the basis of the total watts loss at 50 cycles and a maximum flux density of 10 000 lines per cm^2. When it was the practice to run transformer cores at flux densities around 9 000 lines per cm^2 a test at 10 000 was very useful, but now that the practice in England is to run cores between 12 000 and 14 000 lines per cm^2, whilst our foreign competitors are working at 15 000 and, in some cases, up to 15 500, I should like to suggest that if the data can be obtained it would be much more useful to compare steels in future by the total wattmeter losses at 15 000 lines per cm^2.

Mr. G. C. Marris: Steinmetz evolved his law as an empirical one to cover a certain range of flux densities, and he discusses very fully its defects in one of his books. The present paper appears to me to lead to the valuable and not unexpected conclusion that the Steinmetz formula does not apply except in the range which its author specified and which has been found by experience to be justified, namely between inductions of about 3 000 and 10 000 lines per cm^2. It is interesting to consider as a contrast the range of low flux densities which has been discussed by H. Jordan.* Jordan follows Rayleigh in his argument, basing the form of the hysteresis loop on the equation for permeability, but he provides an alternative expression for hysteresis losses in terms of quantities which are perhaps more fundamental from the point of view of the molecular theory of magnetism, and then shows how this new expression can be linked up with the Steinmetz formula. The main result of Jordan's argument as applied to these weak fields would appear to be that the coefficient in the Steinmetz formula can only be expected to remain constant over a region where the permeability is also constant or approximately so; and for weak fields the index would approximate to 3, which is borne out by experimental work. The permeability referred to is derived from the "tip-top point" curve of the hysteresis loops. From densities of about 4 000 to 10 000 lines, which is the region in which the Steinmetz law has been held to be true, the permeability is in many steels approximately constant, the variations being perhaps 30 or 40 per cent for a particular sample, but with densities as high as 16 000 or as low as 2 000 the permeability is changing more in the neighbourhood of 200 or 300 per cent. It is usually assumed that in the case of low flux densities the hysteresis loop is approximately an ellipse, and so analysis is possible. I think it would be very difficult to apply a similar analysis to the high-flux-density case. In conclusion it seems to me unwise to try to extend the use of the Steinmetz law outside the usually accepted range of flux densities, for an empirical law of this type becomes a source of confusion when its "constants" are allowed to change. It would be better to content oneself with a series of curves of loss and induction at one or two frequencies which would be usable, even if not quite so simply, as a basis for comparing materials.

* *Elektrische Nachrichten-Technik*, 1924, vol. 1, p. 7.

Mr. L. G. A. Sims: I cannot feel certain that the author has been able to place this matter beyond all further doubt, as when he states that his results are liable to increased errors at high flux densities he destroys our confidence in the results which he set out to achieve. He has obtained his correction for flux density in the air space by an arithmetical subtraction, taking simple multiples of the magnetizing force H, namely, $11 \cdot 8\ H$ in the first experiments and $4 \cdot 8\ H$ in the later experiments. At higher frequencies, when the result has been calculated at such high densities by voltage readings taken across the coil N_3, it would not be correct to employ such a correction. The voltage due to the air-space flux and the voltage due to the power loss in the iron are approximately in quadrature, but the effect is greater at higher frequencies, and the arithmetical subtraction cannot then give a correct result. Such an arithmetical method is only sound for tests using direct current, such as the ballistic tests, and not for a.c. tests. I should like the author to assure us that he has considered the question of phase angle at the test frequency in obtaining the voltage across the coil N_3 in Fig. 1. N_3 is not the magnetizing coil, but it is closed through a transformer and a galvanometer, and if there is no error there then a possibility of error in the wattmeter reading still remains. As the wattmeter voltage-coil is connected across N_2 and not N_1, with which the current coil is in series, it seems that there is an error either in the flux calculated from the voltage reading across the coil N_3 or in the reading of the wattmeter. The accuracy of a planimeter in integrating areas in a research of this kind seems questionable. The possibility of variable human error is too great, and it seems that errors of that kind have occurred in some of the results. This appears to be a weak point and diminishes our confidence in the accuracy of the ballistic results. The author might have given his reason why the wattmeter calibration, consisting apparently of one reversed direct-current observation, could not have been carried out on orthodox lines at the test frequency on such apparatus as the Drysdale a.c. bridge. Moreover, the practical value of his work would have been considerably enhanced if he had given experimental results for hysteresis cycles which are not symmetrical about the zero axis of flux density, by considering the case of iron magnetized by a steady current on which is superposed an a.c. component. No information is given as to whether his results apply to the case of rotating masses of metal, such as dynamo and motor armatures, etc. Transformers and choking coils are not generally worked at high flux densities, so it is difficult to see the practical application of the results, but this does not detract from their scientific value. I would suggest that the work be extended to cover the unsymmetrical cycles, and over a frequency band not limited by 50 periods per second, but by the upper audible, or even some higher, frequency.

Mr. H. W. Taylor: Machine designers are inclined to look upon the hysteresis exponent as an empirical

figure and to regard as more important a comparison between figures giving total losses in different qualities of material at specified flux densities. The addition of silicon to steel has three marked effects, (1) to increase the electrical resistance and so to lower eddy-current loss, (2) to lower hysteresis losses, and (3) to increase the permeability at low densities—which effect is more pronounced by the shape of the smaller hysteresis loop—and to lower the permeability at the top of the loop at higher densities. Curves showing loss tests on iron samples are usually based upon apparatus similar to transformers, and losses in this type of commercial apparatus are found to correspond closely to the results of tests made in this way. When, however, any of these materials are used in rotating machinery, and more particularly on turbo-alternators, it is well known that a multiplying factor has to be used to allow for the unequal distribution of the flux across the section of the core. One would, however, expect the total losses when different materials are used to the same design to bear some relation to the laboratory tests on the samples of the materials, but whilst an improvement is found with the higher silicon steels at low densities, at higher densities, say at 80 000 to 90 000 lines per sq. in. (this figure being stated as an average density across the core section), the results have been disappointing and the losses have been found to increase quickly, so that in many cases they show at these densities higher figures than in similar machines built with ordinary unalloyed sheet iron. The reason of this is somewhat obscure and worthy of further investigation, but it is believed that, owing to the peculiarities of permeability mentioned above, the already unequal distribution in the core is further disturbed at the higher mean densities, so giving rise to a considerable amount of high-frequency eddy-current loss.

Mr. Ll. B. Atkinson: I should like to endorse a remark that has been made by one of the speakers, and that was in regard to taking an exponential law with a constant index which fits, or did fit, some curve, and obtaining many deductions from it, but then proving that the so-called constant index is not constant, and being led through a series of evolutions and discussions which have no meaning unless it is constant. The value of any mathematical formula is two-fold, namely, to enable calculations to be made, or to throw some light on physical properties or actions; but when a law, stated to be exponential with a constant index, such as Steinmetz evolved, is taken, then it seems that no object is gained in using such a formula if throughout the curve a different index is required from point to point along the curve. It is clear that the formula will not allow calculations to be made, and it throws no light on any physical properties involved, and so I am of the opinion that the fact that Steinmetz's law is not true should be stated in the paper, as that is really the author's conclusion. Applied in a general manner, the law fits a curve for a little way, but I should have liked to see given in the paper a law which would fit the author's curves.

Mr. F. E. J. Ockenden: I am interested in the method of testing shown in Fig. 1. The use of resistance R_3 is not very clear to me. The author says that in all tests the induced E.M.F. wave in the search coils approximated fairly closely to a sine wave. I am rather surprised at this, having regard to the total resistance in the magnetizing circuit R_3, N_1, W. Would it not have been better to cut R_3 out and maintain the correct magnetizing current by extremely accurate adjustment of the generator voltage? Another source of error which appears likely to occur in this, and indeed in all wattmeter methods of measuring the power loss, is that due to the presence of large 3rd and 5th harmonics in the magnetizing-current wave, the former being likely to be of the order of 30 per cent of the fundamental. This component should of course be absent in the voltage wave consequently traversing the wattmeter as a wattless triple-frequency current, and it seems likely to bias the readings should there be any suspicion of eddy-current effect or of mutual induction between the fixed and moving coils. There is no mention of a condensive shunt being employed to compensate for this latter possibility. An excellent method of measuring power loss, devised originally, I believe, by Dr. C. V. Drysdale, in which the induced E.M.F. is measured on an a.c. potentiometer and compared with that in a standard mutual inductance, would appear to avoid all the aforementioned sources of error and would, I think, lend itself very well to the author's purpose. His method of ascertaining the peak flux by commutating the induced E.M.F. and measuring its mean on a d.c. voltmeter appeals to me as being both simple and ingenious, since, in the case of wave-forms differing much from a sine wave, I have always had to estimate the total flux from a graph of the E.M.F. wave. I think it would be better if N_2 and N_3 were in fact the same coil, since there must surely be some magnetic leakage between them. It must further be difficult to ensure that the commutator behaves perfectly. I mention this because I notice that in Table 2A the author takes the trouble to apply a correction figure of 20 to a B of 5 000, implying that he is sure of the peak flux within less than ½ of 1 per cent, which I should have thought to be a little optimistic.

Mr. A. Campbell (*communicated*): The paper appears to settle definitely the question of the inconstancy of the Steinmetz exponent for flux densities above 10 000. The good agreement between the results obtained by the two totally different methods (ballistic galvanometer and a.c. wattmeter) leaves little doubt that, for the materials tested, the exponent does not remain constant above $B_{max.} = 10\,000$. In a set of samples which I tested many years ago the exponent appeared to vary with a change of $B_{max.}$ much more in some than in others, and there appeared to be a connection between the "ageing" properties of the material and its exponent curve, so that one could predict how a particular sample would age, by merely testing the variation of the Steinmetz exponent. If such a relation could be confirmed it would form a useful criterion of ageing properties and save the trouble of tedious ageing tests. I am inclined to think that there are materials which would show a much more constant exponent than those tested by the author.

Mr. B. G. Churcher (*communicated*): With a few

minor exceptions, the whole of the ground covered by the author was investigated in the Research Department of the Metropolitan-Vickers Electrical Co. in the early part of 1925. The author rightly points out that the variation of the hysteresis "exponent" with induction is far greater than is commonly supposed. With 4 per cent silicon steel and using ring specimens we have found that in general the exponent increases from about 1·7 at $B = 10\,000$ to nearly 3 at $B = 15\,000$, rapidly decreasing values being obtained above $B = 16\,000$. Occasionally values as high as 4 are met with, but these are almost certainly abnormal. T. Spooner * shows that such high exponents are due to the scale which is often found on the surface of high-silicon steel. The scale has a low permeability and a high hysteresis coefficient. At low inductions the permeability of the steel is very high compared with that of the scale, so that the flux and hence the hysteresis loss in the scale is very small. As the induction is increased, the steel becomes saturated, causing the scale to carry an appreciable part of the total flux; hence the total hysteresis loss increases very rapidly. Spooner gives an example in which the exponent at $B = 15\,000$ was found to be 3·04. After the scale had been removed from the specimen by pickling, the exponent fell to 2·36. Further work on this matter is very desirable, using carefully pickled specimens and taking the induction up to $B = 18\,000$. A matter of great importance in the investigation of exponents at high inductions with ring specimens is that the ratio of outside to inside diameter should approach unity as nearly as is practicable. If this precaution is not taken, the values obtained for the exponents will be considerably in error owing to changing distribution of induction over the cross-section of the specimen, which takes place as the degree of saturation is increased. Also, the exponent of the hardened material at the edges of a narrow ring may be different from that of the rest of the material. To obtain accurate results on unannealed ring specimens rather large diameters are necessary and for this purpose we have used rings 73·5 cm outside and 63·5 cm inside diameter, giving a ratio of outside to inside diameter of 1·16 and a width of magnetic path of 5 cm. In my opinion far too much importance has been attached in the past by various workers on this subject to Steinmetz's value of 1·6 for the exponent. They seem to have assumed, without giving any reasons, that there is something fundamental about the value 1·6 and that any other value obtained is to be considered abnormal. The author draws attention to the large errors that can be obtained in using narrow rings or strips (such as those used in the Epstein apparatus) owing to the hardening effect of punching or shearing at the edges of the rings or strips. This is illustrated in Table 15. The effects of punching or shearing can, of course, be removed by annealing but not without altering the general quality of the material as well. For much experimental work and for all acceptance tests in connection with the purchase of sheet steel, the condition of having to anneal specimens before testing them is obviously one that cannot be accepted. For this reason I devised in 1918 an apparatus taking strips 10 cm wide, and the apparatus has been used by the Metropolitan-Vickers Co. for acceptance tests since that time. Besides possessing the required accuracy the apparatus has certain other advantages for routine testing, but these matters cannot be gone into here. With regard to the agreement between the values of hysteresis loss determined ballistically and with alternating current at 50 cycles, the author's observations (Table 15) show differences up to 7·9 per cent, the average difference being about 4 per cent. The a.c. results are consistently higher than the ballistic results. It seems very important that the identity or otherwise of the hysteresis loss at 50 cycles and that determined ballistically should be established, as further work on this subject would be much facilitated thereby. As the author remarks, it is very difficult to obtain a good accuracy in ballistic tests at high inductions owing to the compression of the extremities of the loop, apart from any question of the absolute accuracy in the measurement of B. However, we have found that by adopting a suitable procedure in making the observations and by attending to all possible sources of error, especially those arising in drawing and determining the areas of the loops, we have been able to obtain very consistent results and also good agreement between ballistic and 50-cycle values. The values obtained on a ring specimen of 4 per cent silicon steel are given in Table A.

* *Electric Journal*, 1925, vol. 22, p. 132.

TABLE A.

Hysteresis Loss in watts per kg.

$B_{max.}$	A.C. (50 cycles)	Ballistic	Percentage difference; (A.C. − D.C.)
10 000	1·25	1·24	+ 0·8
13 000	2·12	2·07	+ 2·4
16 000	4·70	4·72	− 0·4
18 000	5·90	5·96	− 1·0

Similar results have been obtained on other materials. Our experience leads us to believe that on materials not exceeding 0·4 mm in thickness (where it is known that the skin effect is small) the a.c. and ballistic tests should give similar results, such differences as are observed being due to experimental errors. The author's method of measuring $H_{max.}$ by means of a mutual inductance and the mean voltmeter is ingenious. If the total current traversing the magnetizing winding of the square be called the "magnetizing current," the R.M.S. value of this current will increase by a small amount for a given induction as the frequency is increased from zero to 50 cycles. This is due to the increase in the current component in phase with the applied E.M.F. and corresponding to the eddy-current loss. For "power" frequencies, and especially at high inductions, the eddy-current component is small and approximately in quadrature with the total current. Its effect on the maximum value of the "magnetizing current" will therefore be small, but, strictly speaking,

one would only expect $H_{max.}$ and H from ballistic tests to be identical for very low frequencies. The figures in Table 14 show that $H_{max.}$ measured by the author's method at 50 cycles is 3·8 per cent greater than H at $B = 10\,000$, but the difference steadily falls to 0·4 per cent at $B = 17\,000$. This is due to the eddy-current component becoming of smaller importance owing to the saturation of the steel. Thus, whilst the author's method is very convenient, it is well to bear in mind the distinction between $H_{max.}$ and the maximum value of what is usually regarded as the true magnetizing field, a quantity which is independent of frequency if skin effect is negligible.

[The author's reply to this discussion will be found on on page 432.]

South Midland Centre, at Birmingham, 27 January, 1926.

Dr. M. L. Kahn: The author's investigation proves that there is no definite relation between power loss in magnetic sheet material and flux densities which can be expressed in a mathematical equation with definite constants. The equation proposed by Steinmetz, on which the author has based his experiments, can only be used if the exponent is varied through the range of densities actually used in practice. Obviously, an equation with a varying exponent cannot be used for determining dimensions of machinery, or solving problems arising in connection with the calculation of electric machines or apparatus. Generally speaking, such a formula is not required, and it is quite sufficient to use curves for the relation of loss to the flux density in magnetic sheet material. Such curves have to be used in any case by the designer of electric machines, as the actual magnetic losses in finished machines or transformers are very much higher than the losses determined on specimens in the laboratory. Losses on specimens are merely of interest as they form a general criterion for determining the quality of the sheet material produced by the rolling mills. For this purpose, usually only the loss at a flux density equal to 10 000 and at 50 periods is taken into consideration, so that the shape of the loss curve is not considered. This actually implies that the losses at other densities are in a definite relation to the losses at a density of 10 000. As the paper clearly proves that this is not the case, it might well be considered whether it is not desirable to modify the present arrangement and to take losses at higher densities into consideration, all the more as the material is usually used more at densities above 10 000 than at densities below 10 000. In this connection I wish particularly to point out that the " marked tendency amongst designers of electrical machinery to employ higher flux densities in electrical sheet steel than have been customary in the past," which the author mentions in the introduction of his paper, is due not so much to the fact that machines are rated higher, as to the great improvements which have been made in the production of low-loss magnetic sheet materials. A further point must not be lost sight of in appraising the value of investigations concerning the relation of hysteresis loss and flux density. In practice the bulk of the iron losses is due to eddy currents and surface stray currents, whilst the hysteresis losses in the iron only contribute a comparatively low percentage of the total loss. On the other hand the general subject of power losses in magnetic sheet steel is of such great importance to the electrical industry that further investigations by the National Physical Laboratory would certainly be of great value. I should like to suggest that an investigation of the effect of annealing punchings after the stamping process would be of considerable interest. Although the laboratories of individual firms have carried out experiments on this matter, so far as I am aware no results have been published up to the present. Apart from this, it might be worth while to see whether it would be possible to develop a testing apparatus for iron losses, on which smaller specimens can be used and a sample of less weight can be tested than with the present standard testing apparatus. This would involve the investigation of the discrepancies introduced by the use of smaller samples. A thorough investigation of the subject may conceivably give definite results of allowance which can be made to account for these discrepancies, and a standard apparatus for smaller weights of material might be developed by the laboratories. With the apparatus at present usually employed, it is only possible to test samples of comparatively large area, so that this can only be used by manufacturers who buy their material in bulk and not for specimens cut out of material which is already punched. There is no doubt that the more investigations made on this important subject, and the more we get to know about it, the better it will be for all concerned, and it is to be hoped that investigations may lead to further improvements in the material available for manufacturers of electric machines and apparatus.

Prof. W. Cramp: The author has placed at our disposal the results of some careful work, but many of us who are designers will look at his results from a severely practical point of view. In this connection it should be remarked that the paper is intended to deal with losses at high flux densities, by which the author apparently means densities exceeding 10 000 maxwells per cm^2. His upper limit appears to be only about 18 000. Now in a.c. design it is seldom that the maximum density exceeds about 14 000, whilst in d.c. work 25 000 is reached in the teeth of traction motors. It follows that the losses discussed in the paper do not much concern the design of a.c. machinery, and on the other hand, for d.c. machines, the density has not been carried nearly far enough to be of practical service. It is well known, for instance, that in traction motors the chief part of the iron loss arises from the teeth, but apart from indicating the probability of a much larger hysteresis loss in this region than would follow from the Steinmetz law, the paper gives no definite help. We must hope that the author

will continue his researches up to a density of, say, 26 000. The fact that these densities occur in d.c. apparatus only, introduces another question, with which the author has not dealt. I refer to the difference between the loss when rotating a mass of iron in a magnetic field and the loss when the iron is stationary and the field has a harmonic variation. The difference between the two cases is generally assumed to be very large. With regard to the general form of the Steinmetz equation, the author's results seem to question the existence of any such law. It is not in accordance with any physical conception of the cause of hysteresis that the loss should be proportional to a fixed power of the density, and it seems to me that the adoption of the Steinmetz expression has, on the whole, held back any real knowledge of the phenomena. All the results given in the paper indicate that the index of B is no more constant at low densities than at high values, and consequently it seems to be time that some new expression, based upon a physical picture of the conditions in the iron, should be developed. Such an expression must lead rather to the loss being dependent upon the intensity of magnetization than upon the density; and it is interesting to note that the author has considered this point, which will become of more and more importance as he deals with higher densities. With regard to the methods of measurement, it is disappointing to find that the wattmeter was only calibrated on one value of direct current. The difficulty of getting accurate readings with a wattmeter on low power factors is well known, and it would have contributed to reliance upon the results if this instrument had been calibrated throughout its range on a Drysdale potentiometer. The resistance marked R_4 in Fig. 1 is also very important, and it would be interesting to know what steps were taken to make sure that the wattmeter calibration did not change on alternating current, as this resistance was increased or decreased. With respect to the use of an electrostatic voltmeter supplied through a transformer, I have found on similar tests that such an instrument is liable to considerable errors. Its capacity, slight though it may be, appears to influence the secondary of the transformer to which it is connected, and it is difficult, unless the wave is of a pure sine form, to get two electrostatic voltmeters on the secondary of the same transformer to read precisely the same value. Again, in connection with the areas of the hysteresis loops, the use of the planimeter gives scope for considerable errors, which can often be eliminated by the use of Newton's rule or other graphical means for determining areas. In stating on page 417 that his results are liable to "considerably increased errors," the author shakes our faith in his figures to an extent which I should think is not justified in view of the care taken. He does not justify his treatment of the Lloyd square as a ring, but possibly he can tell us the magnitude of the errors involved in this assumption. Since so great a difference was observed between the results with the wide as compared with those on the narrow strips, it seems hardly reasonable to regard the effect of cutting as negligible; but in any case this effect would be much reduced as compared with that which exists under normal conditions, since the insulation between the stampings in the tests was so thick. On the whole the paper marks a real advance in our knowledge of the hysteresis loss, but I do not think that any more accurate prediction of this important quantity at varying densities is likely to be reached so long as there is a persistent attempt to put the results in the form given by Steinmetz.

Mr. C. E. Webb (*in reply*): The points raised in the discussion may, I think, be conveniently grouped under five or six heads and I shall, therefore, deal with them in this way rather than by replying to individual speakers.

Accuracy of methods.—Several speakers have suggested possible sources of error arising from the methods employed. Most of these had received consideration and been found to be negligible, whilst in one or two cases the speakers appear to be under some misapprehension as to the operation of the test-set.

Mr. Sims criticized the arithmetical subtraction of the air-flux correction from the apparent flux density in the iron. This is, however, correct to a very high degree of accuracy, for the measurement is based on the reading of V_{mean} obtained by rectifying the secondary voltage. This voltage is made up of two parts, one dependent on $B_{max.}$ and the other on $H_{max.}$, and provided the rectification of each component is complete an arithmetical subtraction is justified. This requires that the two component E.M.F. waves pass through zero simultaneously, i.e. that H and B reach their maxima simultaneously. This condition was assumed to be very nearly fulfilled at ordinary power frequencies, an assumption which was experimentally confirmed in the measurements of a.c. permeability described in Appendix 1, when it was found that the commutator brushes required only a very slight angular displacement between the settings for reading $B_{max.}$ and $H_{max.}$.

The errors suspected by Mr. Sims, due to the effect on the reading of one instrument of the load applied by connecting another on a different winding, were tested for by disconnecting all instruments except one in turn and noting whether the reading of the remaining instrument was affected. No observable effects were detected except when the high-ratio transformer T (Fig. 1) was used, and then a very small effect was noticed. When the transformer was used, therefore, the remaining readings were taken with the transformer disconnected, and it was then switched on for the form-factor measurement only. Prof. Cramp also suggested a possible error due to the influence of the electrostatic voltmeter on the high-ratio transformer. No such effect was noticed, although checks were made using two voltmeters of different patterns and of widely different ranges with various ratios on the transformer. As a matter of fact, however, most of the measurements and all those above $B = 14\ 000$, in which the most distorted waves were likely to occur, were made without the transformer and with the voltmeter connected directly to a secondary winding of the square. Checks between these results and those obtained using the transformer also showed no appreciable discrepancy attributable to the influence of the voltmeter on the transformer.

Mr. Sims and Prof. Cramp have both criticized the

use of the planimeter and the use of a d.c. method for calibrating the wattmeter. On the first point it should be mentioned that the loops at high values of B, which are the most irregular in shape, were all plotted in two, three or even four sections, suitable scales for H and B being chosen for each section. Further, the possibility of variable human error was practically eliminated by running round each loop at least three times, rejecting any markedly discrepant result and averaging the remainder. The variation between successive readings was normally considerably less than 1 per cent. The planimeter method was also checked in several cases by the laborious but unassailably reliable method of counting squares, and again agreement was obtained to about ½ per cent, which is definitely within the limits of accuracy of the measurements. With reference to the calibration of the wattmeter, it should be pointed out that the method employed allows of greater accuracy being obtained than an a.c. potentiometer, since the calibration of the latter depends in the last resort upon exactly those standards which were used directly in the method of wattmeter calibration described. It is true, however, that the wattmeter calibration might be different on alternating current from the d.c. value, and it should have been made clear that this had been investigated previously and the instrument found to give concordant results by direct current and alternating current within a fraction of 1 per cent, and that the calibration referred to was only intended to allow for the day-to-day variations in the sensitiveness of the instrument due to temperature and other variable conditions. A closely related point mentioned by Prof. Cramp is the purity of the wattmeter pressure-coil resistance R_4. This was a specially prepared resistance, and it was checked first by replacing it by other resistances known to be of high purity, including a Duddell-Mather anti-capacity resistance, and secondly by taking the same reading under actual working conditions using different wattmeter multipliers (i.e. various values of R_4) and simultaneously altering the number of turns in the secondary winding, N_2, to give the same wattmeter deflection. No perceptible error due to R_4 could be detected by either of these tests.

Mr. Ockenden has questioned the use of a series resistance R_3 in the magnetizing circuit. It is, however, pointed out in the paper on page 414 that the adjustment to the correct magnetizing current was made, as he suggests, by varying the alternator field, and that the resistance R_3 was introduced deliberately to distort the E.M.F. wave. In fact, at each value of frequency and B a reading was first taken with R_3 cut out to give as close an approximation to a sine wave of induced E.M.F. as was obtainable, and then a series of further readings was obtained with increasing values of R_3, and consequently increasing form-factors, to enable a curve connecting watts per kg and (form-factor)^2 to be drawn and an extrapolation made to give the loss for an exact sine wave of E.M.F. Mr. Ockenden also referred to the effect of third and fifth harmonic components of the magnetizing current. The wattmeter takes proper account of these components and measures the losses due to them on the sole condition that the wave-shape of B is not re-entrant, i.e. that there is no subsidiary loop on the main loop. Error might, of course, be caused, as Mr. Ockenden suggests, by the presence of eddy currents or mutual induction between the wattmeter coils, but the former were avoided by the absence of metal from the case of the instrument and the latter by suitable adjustment. Tests made at much higher frequency showed that any effect from these causes with a fundamental of 50 periods per sec. must be very small. The potentiometer method of measuring iron losses is, I believe, really due to Mr. Campbell, and makes use of a mutual-inductance bridge; but this method suffers from the very defects which Mr. Ockenden suspects in the wattmeter method, since the losses are referred to the fundamental component of the flux wave whilst the true $B_{max.}$ cannot be determined, since the wave cannot be definitely adjusted to be a sine wave. The wattmeter method and the a.c. potentiometer method really have different spheres of usefulness. The latter method commences where the former method becomes inaccurate on account of lack of sensitivity. The border line occurs in the region where $B = 200$. At lower values of B than this amount, the changes of permeability are not very great, so that B does not differ much from a sine wave with a sine wave of H. It is in this region of low values of B that the a.c. potentiometer methods are specially useful.

With reference to Mr. Ockenden's remarks on the use of the commutator, he is correct in assuming that very great care is needed to secure satisfactory behaviour, but with constant attention to the brushes and continuous lubrication during operation it is believed, from the results of tests carried out, that the error on the determination of $B_{max.}$ does not exceed 2 parts in 1 000. The correction of 20 with $B = 5\,000$ is therefore justifiable as being definitely greater than the probable error of measurement, but the further correction of 10 on 10 000 given in Table 5A is within the limits of experimental error and is only stated to show the magnitude of correction involved at this value of B.

Prof. Cramp's query as to the justification for treating the Lloyd square as a ring is dealt with in Appendix 3, and, as pointed out there, the very close agreement between the ballistic results on strips (in the Lloyd square) and rings, after annealing together, indicates that the error involved in such treatment is not greater than the errors of measurement—about 1 per cent.

Both Prof. Cramp and Mr. Sims referred to the disquieting effect of the suggestion that "at high flux densities the results are liable to considerably increased errors." Possibly the expression was an unfortunate one to use, but it should be noted that it had reference to the tests on the preliminary investigation carried out on the original Lloyd square—in the new square alterations in design were made to reduce to a minimum this tendency to increased errors at high flux densities. Actually a comparison between the results given in Table 4 using the old square and those in Tables 7, 9, 11 and 13 for the same specimens using the new square shows that the former were not very seriously in error due to these causes. The statement was introduced, however, because it was particularly desired to emphasize the fact that a test-set giving thoroughly reliable results at low flux densities may be subject to quite

serious errors at higher flux densities unless certain corrections, which are negligible in the first case, are carefully made.

Whilst, therefore, the methods employed are believed to be not open to serious criticism on *a priori* grounds, a conclusive justification of their accuracy is provided, as pointed out by Mr. Campbell, by the very close agreement between the results obtained by two such entirely distinct methods. I was also very much interested to learn that Mr. Churcher had obtained results so closely agreeing with those given in the paper.

Influence of scale.—Mr. Holbrook and Mr. Churcher both referred to the influence of the presence of scale on the variation of the exponent of B for the hysteresis loss. I was aware of Mr. J. D. Ball's suggestion, but did not mention it as the reference to the subject in his paper was very brief and not supported by full data. Mr. Spooner's work, which is given in greater detail, had escaped my notice. Moreover, my own tests on this point, though unfortunately very limited in range, did not confirm their conclusions. To investigate the effect of scale, specimen No. 3A was very carefully pickled and the complete tests on it were repeated. The final results are given in Table B, which is directly comparable with Table 9.

It will be seen from this comparison that the effects of removing the scale are :—

(*a*) To reduce the apparent loss—due of course to the removal of the low-permeability scale, the more uniform distribution of the flux across the section of the remaining plate, and the consequent lower flux density in the high-permeability steel.

(*b*) To reduce to a negligible amount the discrepancies between the ballistic, 25-period and 50-period results. This suggests that the rather large discrepancies (up to 7·9 per cent) between ballistic and a.c. values of hysteresis loss, also pointed out by Mr. Churcher, are due to the presence of scale and are not inherent in the method of testing. Presumably the flux distribution is different in the ballistic and a.c. tests when scale is present.

(*c*) The maximum values of the exponent of B for hysteresis loss are not appreciably less than before, but the increase in the exponent takes place at rather higher values of B. This is accounted for, as in (*a*), by the actual flux density being somewhat higher than the apparent value when scale is present.

TABLE B.

Comparison of Results on Specimen No. 3A after pickling.

B	Total loss in $\frac{\text{watts}}{\text{kg}}$		Hysteresis loss in $\frac{\text{watts}}{\text{kg}}$			Exponent of B for hysteresis loss		
			At 50 ~ per second					
	At 25 ~	At 50 ~	From 25 ~ results	From 50 ~ results	From static loops	25 ~	50 ~	Static
10 000	1·11	2·67	1·68	1·69	1·70			
						1·82	1·74	1·78
12 000	1·52	3·69	2·34	2·32	2·35			
						2·19	2·18	2·06
14 000	2·10	5·09	3·28	3·25	3·23			
						2·58	2·60	
15 000	2·50	5·97	3·92	3·89	—			2·76
						2·81	2·72	
16 000	2·94	6·99	4·70	4·64	4·67			
						1·74	1·77	1·69
17 000	3·30	7·78	5·22	5·16	5·17			
						1·17	1·30	—
18 000	3·58	8·45	5·58	5·56	—			

It therefore appears from these tests that the increase in the exponent is not a spurious effect due to the presence of scale but a genuine property of the material, although a larger number of tests on this point would be desirable to confirm the results obtained on specimen 3A.

Effects of cutting and annealing.—I should like to endorse very strongly Mr. Churcher's remarks on the importance of using wide specimens to minimize the effect of cutting on the magnetic properties of the material. It is believed that the width of 7 cm used at the National Physical Laboratory is sufficient to reduce such effects to a very small percentage, but any departure from this width should certainly be in the direction of increasing rather than decreasing it.

Mr. Holbrook asked whether similar information to that given in Table 15 for the effect of annealing medium-resistance material after cutting was available for other material. No such complete data have been obtained on high-resistance material, but a few isolated tests that have been made indicate results of a very similar nature.

Conditions of testing material.—Dr. Kahn and Prof. Cramp have both pointed out that the losses in machines are much greater than and, to a considerable extent, of a different nature from those resulting from the alternating magnetization applied in the test-set. This was, of course, fully realized, and also the fact that an extension to flux densities above 18 000 was very desirable. At the same time, the methods used in the investigation are those by which the suitability of material is gauged in practice, whilst it seems reasonable that results up to 18 000 should give a better indication of the behaviour of the material under densities of 20 000–25 000 than values at 10 000 only. It is hoped later to carry the tests up to still higher values of B, but the experimental difficulties of making these measurements under standard conditions become very great above about $B = 18\,000$.

It seems doubtful whether any change in the general method of testing sheet material for losses can be satisfactorily made, but I agree with Mr. Holbrook and Dr. Kahn that the results in the paper point to the desirability of testing material to be used at high flux densities at, say, $B = 15\,000$ in addition to $B = 10\,000$. Dr. Kahn's further proposal of tests on smaller samples deserves careful consideration, although such methods would probably only be suitable for rough workshop tests and not for high-accuracy standard tests.

The further work suggested by Mr. Sims on unsymmetrical cycles, rotating hysteresis and losses at telephonic frequencies, would be of great value but lies outside the scope of the present paper. Mr. Campbell's results relating to "ageing" are of great interest, but I have had no experience on this point and cannot therefore offer any confirmation of them.

With reference to the method of measuring a.c. permeability described in Appendix 1 to which Mr. Churcher draws special attention, I should like to mention that the idea of this was suggested to me by Mr. D. W. Dye. It is, of course, theoretically open to the objection pointed out by Mr. Churcher, but normally the alteration produced by the eddy-current component is exceedingly small. The figures given in Table 14 were obtained when very little experience had been gained with the method, and it is believed that the discrepancies in the ballistic values were largely due to one or two small errors not inherent in the method which have since been eliminated. Later results show an agreement to within 1 per cent between the a.c. and ballistic permeabilities.

Law of variation of hysteresis loss with B.—Several speakers have drawn attention to the fact that Steinmetz's law is admittedly an empirical one only applicable between fairly narrow limits of B and not to be expected to hold true outside those limits, and that, in practical designing, reliance must be placed on curves of loss. This was, of course, fully appreciated, but I felt that it was desirable to emphasize the departure of the law of variation of hysteresis loss with B from Steinmetz's law at high values of B, because I am strongly of the opinion expressed by Mr. Churcher and Prof. Cramp that the 1·6-power law has been given altogether undue importance and that this has probably done a great deal to retard progress in our knowledge of the subject.

I hope and believe that I have not been guilty of the mathematical solecisms suggested by Mr. Atkinson. The exponential form of stating the results was employed for the purpose just mentioned of emphasizing the magnitude of the deviation from the Steinmetz law, and I do not think any unjustifiable deductions have been drawn from this form of statement. The ratio of variation, or exponent as I have called it, may be used quite legitimately to show the way in which loss varies with B over any definite range of B.

I fully agree that a law of a different type which will fit the curves obtained is urgently needed to enable prediction of losses at higher values of B to be made, but although I have attempted to discover such a formula I have not succeeded in evolving any reasonably simple expression which will accord with the experimental results and I have, therefore, thought it better not to introduce any tentative formula which might only be misleading. Jordan's work at low flux densities, referred to by Mr. Marris, is of interest in this connection, but I agree with him that it is unlikely that the same principles could be applied satisfactorily at high values of B.

Results which I have obtained also indicate that for other magnetic materials the exponent is much more constant, as suggested by Mr. Campbell. For such materials, therefore, Steinmetz's law may be safely used, but it is probable that if a new form of law based on the physical actions taking place can be discovered, it will be applicable by a suitable choice of constants both to such materials as those tested in this investigation and to those having a much more constant exponent of B.

ANNUAL DINNER, 1926.

The Annual Dinner of the Institution was held at the Hotel Cecil on Thursday, the 11th February, 1926, when the President, Mr. R. A. Chattock, presided over a gathering numbering about 580 persons.

Among those present were: The Rt. Hon. Neville Chamberlain, M.P. (*Minister of Health*), The Rt. Hon. Sir A. Steel-Maitland, Bart., M.P. (*Minister of Labour*), The Rt. Hon. Lord Hewart (*Lord Chief Justice*), The Rt. Hon. The Viscount Falmouth (*Member of Council*), Air Chief Marshal Sir H. M. Trenchard, Bart., G.C.B., D.S.O. (*Chief of Air Staff, Air Ministry*), Sir H. Hirst, Bart., Sir F. Mills, Bart., D.L. (*President, Iron and Steel Institute*), Sir John Snell, G.B.E. (*Past-President, I.E.E., and Chairman, Electricity Commission*), Rear-Admiral Sir A. E. M. Chatfield, K.C.B., K.C.M.G., C.V.O. (*Third Sea Lord and Controller of the Admiralty*), Sir S. Chapman, K.C.B., C.B.E. (*Permanent Secretary, Board of Trade*), Brig.-Gen. Sir W. T. F. Horwood, K.C.B., D.S.O. (*Chief Commissioner, Metropolitan Police*), Maj.-Gen. Sir W. Childs, K.C.M.G., K.B.E., C.B., Sir P. Nash, K.C.M.G., C.B., Sir W. S. Abell, K.B.E. (*Chief Ship Surveyor, Lloyd's Register of Shipping*), Sir J. Devonshire, K.B.E. (*Vice-President*), Sir H. Fowler, K.B.E. (*Vice-President, Institution of Mechanical Engineers*), Sir L. Macassey, K.B.E., K.C., M.A., LL.D., Sir A. B. Gridley, K.B.E., Sir J. E. Petavel, K.B.E., D.Sc., F.R.S. (*Director, National Physical Laboratory*), Sir H. Gibson, Bart. (*President, Incorporated Law Society*), Sir H. Haward (*Vice-Chairman, Electricity Commission*), Sir M. Hughman, Colonel Sir J. Nall, D.S.O., T.D., M.P. (*President, Institute of Transport*), Sir W. Noble, Sir E. Rutherford, O.M., F.R.S. (*President, Royal Society*), Sir St. Clair Thomson, M.D., F.R.C.S. (*President, Royal Society of Medicine*), Sir O. E. Warburg, O.B.E., M.A., J.P. (*Chairman, London County Council*), The Hon. H. P. Colebatch, C.M.G. (*Agent-General for Western Australia*), The Hon. John Huxham (*Agent-General for Queensland*), Col. E. Snowden (*Agent-General for Tasmania*), Mr. C. T. Allan (*Hon. Secretary, Western Centre*), Mr. P. F. Allan (*Hon Secretary, North-Eastern Centre*), Mr. Ll. B. Atkinson (*Past-President*), Councillor H. K. Beale (*Chairman, Birmingham Electric Supply Committee*), Colonel R. E. B. Crompton, C.B. (*Past-President, Honorary Member and Faraday Medallist*), Mr. R. N. Eaton (*Hon. Secretary, Irish Centre*), Lieut.-Col. K. Edgcumbe, R.E. (T.A.) (*Vice-President*), Mr. A. R. Everest (*Chairman Designate, British Electrical and Allied Industries Research Association*), Dr. S. Z. de Ferranti (*Past-President, Honorary Member and Faraday Medallist*), Prof. C. L. Fortescue, O.B.E. (*Member of Council*), Mr. H. Cecil Fraser (*Hon. Secretary, North Midland Centre*), Mr. G. R. Freeman (*President, Institute of Chartered Accountants*), Mr. R. W. Gregory (*Chairman, North-Eastern Centre*) Mr.R.Grierson (*Member of Council*), Mr. H. H. Harrison [*Past Chairman, Mersey and North Wales* (*Liverpool*) *Centre*], Mr. H. Hastings (*I.E.E. Local Hon. Secretary for Spain*), Mr. J. S. Highfield (*Past-President*), Mr. W. E. Highfield (*Member of Council*), Mr. H. Hooper (*Hon. Secretary, South Midland Centre*), Mr. G. W. Humphreys, C.B.E. (*Chief Engineer, London County Council*), Mr. J. E. Kingsbury, Prof. H. Lamb, M.A., D.Sc., LL.D., F.R.S. (*President, British Association*), Mr. H. C. Lamb (*Past-Chairman, North-Western Centre*), Monsieur M. Leblanc (*Vice-President, Société Française des Electriciens*), Mr. E. Leete (*Member of Council*), Mr. G. C. Lloyd (*Secretary, Iron and Steel Institute*), Mr. A. L. Lunn (*Hon. Secretary, North-Western Centre*), Mr. A. MacGregor, M.D. (*President, Electro-therapeutic Section, Royal Society of Medicine*), Mr. S. Machin, J.P. (*President, Association of British Chambers of Commerce*), Mr. S. W. Melsom (*Member of Council*), Mr. L. W. Migotti (*Past-Chairman, Argentina Centre*), Mr. R. B. Mitchell (*Past-Chairman, Scottish Centre, and President, Incorporated Municipal Electrical Association*), Mr. E. W. Monkhouse (*Chairman, Association of Consulting Engineers*), Colonel R. K. Morcom, C.B.E. (*Chairman, British Electrical and Allied Manufacturers' Association*), Mr. W. M. Mordey (*Past-President*), Brig.-Gen. M. Mowat, C.B.E. (*Secretary, Institution of Mechanical Engineers*), Mr. A. Page (*Vice-President*), Mr. R. W. Paul (*Member of Council*), Mr. S. L. Pearce, C.B.E. (*Electricity Commissioner*), Col. T. F. Purves, O.B.E. (*Member of Council, I.E.E., and Engineer-in-Chief, G.P.O.*), Mr. W. R. Rawlings (*Vice-President, Illuminating Engineering Society*), Mr. C. Rodgers, O.B.E. (*Member of Council*), Mr. P. Rosling (*Member of Council*), Dr. A. Russell, M.A., D.Sc., LL.D., F.R.S. (*Past-President*), Mr. E. H. Shaughnessy, O.B.E. (*Member of Council*), Mr. F. E. Smith, C.B.E., F.R.S. (*President, Physical Society of London*), Mr. R. T. Smith (*Past-President*), Mr. E. F. C. Trench, C.B.E. (*Vice-President, Institution of Civil Engineers*), Mr. S. J. Watson (*Member of Council*), Mr. W. B. Woodhouse (*Past-President*), and Mr. P. F. Rowell (*Secretary*).

The President read the following message from Monsieur Legouez, President of the Société Française des Electriciens:

> "I thank the Institution very heartily for its very kind invitation to the Annual Dinner which, to my great regret, I am not able to attend. Our Vice-President, Maurice Leblanc, will represent the Société Française des Electriciens, and I join him in offering to you the fraternal greetings of the electrical engineers of France and in expressing their desire for an ever closer and still more cordial co-operation."

The Toasts of "His Majesty the King" and "Her Majesty the Queen, His Royal Highness the Prince of Wales, and the Other Members of the Royal Family" were proposed by the President and loyally received.

The Rt. Hon. Neville Chamberlain, M.P. (*Minister of Health*), in proposing the toast of "The Institution of Electrical Engineers," said: "I believe that it is

some 55 years since the foundation of the Society of Telegraph Engineers, which was, I am informed, the original title of this Institution. During that half-century the growth in its membership, in its usefulness and in its influence, has kept pace with the remarkable and manifold developments in the use of electricity itself. I am told that the membership now exceeds 12 000, and that you are actually the largest Institution in this country. I do not know whether there is any agent on behalf of which so many extravagant claims have been made as on behalf of electricity—not, I need hardly say, by the members of this Institution, but by a public whose enthusiasm is only equalled by its ignorance. All the same, however, if we look back I do not know but that the reality is pretty well equal even to the anticipation. In domestic lighting, electricity is now unrivalled; in transport, it is rapidly taking a leading place, and for the ease of its transmission and its freedom from smoke and noise, it is becoming the most popular form of power in almost every branch of manufacture; whilst the development of telephony and of broadcasting shows that electricity is entering into the lives of the whole community, and one is tempted to ask where it is going to stop. Will it leave us any privacy whatsoever? Apparatus has been produced which photographs our insides, and the other day I saw in an illustrated paper a picture of apparatus which, it was stated, would enable anyone to see what was going on in the next room through a lath and plaster partition. It only remains—and I fancy that electrical engineers are capable of it—to invent a new camera which will photograph our thoughts. If you do that, whilst we already know what you think of us, we politicians will have some satisfaction in realizing that you will know what we think of you. It has long been obvious to the Government, in view of these considerations, that it would be necessary in self-defence to find you something else to do, and accordingly we have announced that we are going to bring in an Electricity Bill. I do not know what you think of it, but the first sketch of the proposals has been welcomed by the public with a unanimity that has rather alarmed me. The only thing which consoles me is that the Bill is praised quite as much for what it does not do, as for what it does do. To begin with, there is no subsidy, and there is to be no nationalization; there is to be, in fact, as little State interference as is compatible with the purposes we have in view. I think I may, from the layman's point of view, express our purpose as being threefold: to provide for a concentration of production, for the pooling of power reserves, and for the standardization of equipment. I believe that if we can achieve these three things we may hope to see throughout the country a considerable cheapening of electricity, and certainly a very much more available supply. I hope it will be agreed that aims of that kind are worth a serious national effort. We cannot, of course, make such changes without interfering with local and personal interests. Certain stations will have to be closed; there will be a certain amount of dislocation and change, and possibly an abolition of existing offices. What we desire, however, are changes which we believe to be in the national interest and of benefit to the community as a whole, and what is of benefit to the community as a whole must sooner or later percolate right through to every individual part of it. In the carrying out of our proposals after they have been passed through Parliament we shall look to electrical engineers for assistance, and I feel confident that we shall receive it. I only want to say further that I have been especially looking forward to being here to-night, because I knew that Mr. Chattock would be in the Chair. He is an old friend and colleague of mine. During the early part of the war, he was in charge of the Electricity Supply Department of the City of Birmingham and I happened to be Lord Mayor. It was my duty to share in his responsibilities in what was a very difficult time. We had turned our city into a munition factory; the demands on us came every day with increased vehemence. Our difficulties in connection with staff and with fuel were overwhelming, and it was an enormous satisfaction to me to see the courage and the determination with which Mr. Chattock faced those difficulties and ultimately won through to success. He is in the seat of the mighty to-night, and I wanted to see him there and pay my tribute to his worthiness to occupy it. I ask you to drink the health of the Institution of Electrical Engineers, coupled with the name of its President, Mr. R. A. Chattock."

The President, in responding, said: "I want to thank you for the very hearty way in which you have received this Toast. We have been told for many years that we are still in our infancy, but I think we ought to grasp the fact that we are now considerably over 50 years of age. In spite of our age, however, we are still growing. The Institution has now in the scientific world a standing and importance which are second to none, and I am very glad indeed to know how its members are supporting it and what a great deal they think of it. It is only by devoting ourselves to the work of the Institution that we can further its interests, and that devotion is to me very apparent in all its members. I know that there are one or two grumblers; occasionally one hears the remark: 'What has the Institution done for me?' Well, we are the Institution, and when a question like that is asked we can only say: 'What are we doing for ourselves?' I have no patience with those who want others to do for them things which they should do for themselves. I want to thank the proposer of this Toast for the very kind and appreciative way in which he spoke of the Institution and also of myself. I can assure him that this Institution is willing and anxious to do everything it can to further the interests of the great industry which we represent, and if we can help the Government in any way I am sure that we shall do so to the best of our ability. Approximately one hundred years ago the steam age commenced, and that age revolutionized all the ideas and habits of those days. We are now inaugurating the electrical age, and it would be a bold seer who would prophesy what will be the ultimate changes which this age will bring to us. I feel that we are only on the fringe of enormous developments. Mr. Neville Chamberlain referred to the marvels of wireless telegraphy, and in that connection I should like to

mention that last month the Marconi Company sent by wireless my signature and greetings to the American Society of Engineers across the Atlantic. The resulting photograph was forwarded to me the other day, and I can testify that the signature has not been forged. I am particularly pleased that Mr. Neville Chamberlain was able to find time to come here to-night and I want to extend a very hearty welcome to him and to Sir Arthur Steel-Maitland, who is another Birmingham stalwart chosen by the Prime Minister to assist him. Mr. Chamberlain referred to his connection with me in the Birmingham Corporation. We had great difficulties in those days, and I should like to take this opportunity of thanking him again for brushing them away in a manner that only he could do. In doing that, he enabled us to construct and equip a 10 000-kW generating station in nine months, which I think was an excellent performance during that difficult time. Mr. Chamberlain is now in charge of the health of this country, and I am certain that he is fully cognisant of the extraordinary influence that electricity is having on the amelioration of the conditions under which we live and work. He has mentioned cheap and quick transport and the abolition of smoke, but I want to remind him that electric homes are bright and clean, and that electric cooking is wholesome and excellent; with electric cooking the nutritious part of the food is not dissipated up the chimney as in other methods. Workshops are made healthy by the abolition of fumes in their furnaces and processes. These are only some of the blessings which electricity brings. The direction of it is in our hands and we must follow it up and make the fullest possible use of it. I cannot let this occasion pass without referring to the youngest activity of the Institution—its Wireless Section. I have attended several of the meetings of that Section, and have been impressed by the very great enthusiasm and intelligence which are brought to bear on the conduct of its meetings and the reading of its papers. I wish it the greatest success in London and throughout the country."

Mr. W. B. Woodhouse (*Past-President*) then proposed the Toast of "Our Guests," to which the **Rt. Hon. Sir Arthur Steel-Maitland, Bart., M.P.** (*Minister of Labour*), and **Sir Lynden Macassey, K.B.E., K.C.,** responded.

A reunion was subsequently held in the Victoria Hall of the Hotel.

RECENT IMPROVEMENTS IN THE INSULATION OF ELECTRICAL MACHINERY.

By K. G. Maxwell and Allan Monkhouse, Members.

(*Paper first received 28th January, and in final form 30th March,* 1925; *read before* The Institution 23*rd April and before the* North-Eastern Centre 14*th December,* 1925.)

Summary.

The paper constitutes a review indicating the more recent developments in the manufacture and use of insulating materials. A survey of the prominent characteristics of such materials is followed by a summary of process improvements. In handling this subject the authors put forward a strong plea for standardization of nomenclature and of test methods for determining essential properties of insulating materials. The paper is accompanied by eight appendixes, which include examples of standardizing of material terminology and a considerable amount of data obtained by test methods as adopted by the E.R.A.*

During the past 20 years singularly little change has been observable in the general nature of the insulating materials available for the insulation engineer's requirements. Perhaps the only really outstanding new materials are those which have resulted from the introduction to electrical work of synthetic resins of the phenolaldehyde type. As evidence of this statement—if any is required—we have here a book of samples drawn from standard insulating materials in use in 1903, beside which are mounted examples of the best corresponding products available at the present day.

It must not, however, be inferred that there has not been any improvement in the insulation of electrical machinery and apparatus during the same period. On the contrary, the past few years have been marked by:

(1) Clearer understanding of the theories of insulation, resulting in a more scientific use of the materials available.

(2) Closer knowledge of the properties of the various materials under extreme thermal, mechanical and electrical conditions.

(3) A definite movement to develop standardized methods of ascertaining and expressing values for the properties of the various insulating materials.

(4) Organized effort to produce refinements in the quality of insulating materials.

(5) Improvements in the method of applying insulating materials in the electrical manufacturers' works, involving close scientific control for insulating processes.

It is proposed to deal with each of the above phases of development under the following headings:—

1. Theories bearing on insulating problems.
2. Data in regard to properties of insulating materials.
3. Standardization of methods of testing insulation.
4. Progress towards improvement of insulating materials.
5. Improvements in processes of application of insulating materials.

* British Electrical and Allied Industries Research Association.

1. Theories Bearing on Insulating Problems.

The literature bearing on the behaviour of dielectrics when under electrical stresses has been appreciably enriched during the past few years by valuable contributions by investigators in almost all countries where electrical development is in progress. Appendix 8 is a bibliography of the more important treatments of this subject. In addition to the work done by the investigators, whose writings are referred to in the bibliography, much organized research is being undertaken by various national research institutions. The Committee on Electrical Insulation of the Division of Engineering of the National Research Council (of America) has issued a report outlining its extensive programme of systematic research, noting the problems connected with electrical insulation. According to the annual report of the British Electrical and Allied Industries Research Association, a similar investigation on less extensive lines is already under development in this country.

Much that has been published is more of academic interest at the moment than of actual practical value to the industry, and it is therefore not proposed to deal further with this phase of the subject.

2. Data in Regard to Properties of Insulating Materials.

The temperatures and general conditions under which insulating materials have to operate are very largely determined by the various national and international rating rules now in force. Appendix 2 sets forth a scheduled comparison of the better-known rating rules. These rules, so far as Great Britain is concerned, are only now emerging from the melting-pot. B.E.S.A. Specification No. 168 has recently superseded the old Specification (No. 72) and has helped partly to fill a badly felt need for standard information on insulating materials. A specification is now in preparation which will further supplement the information available. In the meantime, however, it is clear that the electrical industry as a whole is awaiting reliable information with regard to the behaviour of insulating materials offered as insulators under the extreme electrical, thermal and mechanical conditions permissible in electrical machinery and apparatus. It is

perhaps reasonable to anticipate that one of the results of the valuable work now being done by the E.R.A. will be to provide the industry with this information.

In the preparation of such data the question of ageing and life tests should be considered as being of prime importance. The effects of continued exposure to conditions representing operating conditions in machines has only been superficially dealt with in the past. It is here suggested that tests of this nature should include a study of the effects of vibration, moisture and sustained electrical and mechanical stresses, all at the extreme temperatures likely to occur in practice. In Appendix 1 an endeavour has been made to set forth in tabular form some of the properties of the insulating materials in general use.

3. Standardization of Methods of Testing Insulation.

While discussing the provision of standard data on insulating materials, the necessity of standardized methods of test cannot be too highly emphasized. Such methods are now being published by the E.R.A., and it is to be hoped that the methods recommended will rapidly be adopted by all who test insulating materials. So far, however, these test methods are only applicable to raw materials and not as a general rule to finished apparatus. Some definite policy in regard to the latter is very necessary, particularly in respect to the so-called high-pressure or flash tests. The generally accepted practice at the present day is to apply to insulation a flash test of 2 to $2\frac{1}{2}$ times nominal full voltage for a period of several minutes while the machine or apparatus is still hot after its initial trial run. At no time in the life of a machine is its insulation so vulnerable as when it has just completed its first temperature run. The windings—particularly end windings—contain certain volatile matter which rapidly dries up in service, but which during an initial 6 hours' run has just had time to leave the hotter portions of the material and concentrate where the windings are coolest. A flash test then breaks down what is probably a perfectly sound machine, and thus necessitates a "re-wind" where a "drying out" is all that is necessary. The leakage-loss test described by Hartshorn * appears to afford an ideal way of avoiding many unnecessary failures in testing large plant and apparatus. The suggestion made by Mr. Hartshorn to use a bridge method of measuring leakage losses on such apparatus gives a practical solution of the problem which, in the authors' view, could never have been solved by using wattmeter methods. In a test of this kind, a disproportionate rise in a leakage current gives an indication of a failure commencing in time to check an actual breakdown, and thus gives the insulation a chance of another "drying out" before applying the full test.

Before passing from the subject of standardization as applied to insulating materials, the authors wish to draw attention to Appendix 3, which gives a classification of insulating materials with both trade and abbreviated standardized names. This table was developed by a British firm in 1922 to permit the employment of one set of material designations on drawings, specifications and in the shops. It is included as a sample of successful standardization although it is recognized that many of the terms then adopted do not agree with those more recently adopted by the E.R.A. The universal adoption of a complete list on this basis will go far towards eliminating the present confusion which exists between the producers of insulating materials, manufacturers and users of electrical plant. Up to date, there is no detailed classification of insulating materials under the E.R.A. class recognized by the B.E.S.A. The only guide is the general indication which has been given by the International Electrotechnical Commission rating rules. It is announced in the appendix to B.E.S.A. Specification No. 168 that the E.R.A. now have in hand a standard grouping (and nomenclature) which sooner or later will become available.

* *Beama*, 1923, vol. 13, p. 89.

4. Progress Towards Improvement of Insulating Materials.

(*a*) I.E.C. Class O and Class A Materials.

The development of oil-immersed transformers and switchgear has given a great impetus to the improvement of materials of this class.

(1) *Papers and Pressboards.*—Until the latter part of the war, comparatively little scientific study had been given in this country to the production of high-grade insulating papers and pressboards. The pressboard used in the manufacture of shell-type transformers was frequently the common board made for the wool-finishing industry and similar work. Recent research, however, has resulted in perfectly definite conclusions being reached as to the relative superiority of various commercial vegetable fibres for electrical work, and also as to the most suitable methods of converting the same into boards for the requirements of the industry. Table 1 shows the average results of a very large number of tests on the behaviour of special papers made from various fibres. The overwhelming superiority of cotton for high-temperature work is clearly demonstrated, and as cotton is the only fibre of those tested which is entirely free from lignin in its structure, this result might be expected. The highly lignified fibres, including jute, deteriorate seriously at temperatures over 80° C.

Another most interesting development is the manufacture of pressboards possessing widely differing properties, making them applicable to specific requirements. Table 2 shows some characteristic figures taken on various special pressboards which have already been produced on a commercial basis. The authors consider that finality in this direction has not by any means been reached and that insulators of the pressboard class may ultimately largely replace those belonging to the so-called laminated-paper class. Efforts to introduce leather cuttings, rubber latex and other similar materials into the manufacture of pressboard for electrical work has not so far been

attended with success, due to the inability of these materials to resist high temperatures without ageing.

(2) *Fabrics, tapes, etc.*—With the exception of one or two isolated cases, the electrical industry has been content to carry on with such fabrics, tapes, etc., as the dealers in this class of goods have been able to offer. Speaking generally, the materials in use are not of high quality, and improvement in this direction can hardly be expected until manufacturers in general are prepared to pay the additional price for a superior article. A recent innovation is the introduction of artificial silks, but the application of this material to the electrical industry is at the moment too much in its infancy to predict whether it will become general. One thing which is certainly in favour of this material is its low moisture-absorption figure.

(3) *Coverings for wires.*—Cotton, silk, paper, enamel and asbestos are all extensively utilized as coverings for wires in electrical work. Artificial silk and so-called "spun glass" (glass wool) are also being tried for this purpose.

Cotton, however, remains the most important wire-covering material, and it is regrettable that so little has apparently been done to attempt to improve the insulation value of the cotton yarns which are applied to wires. Possibly this is due to the fact that the majority of engineers regard the cotton covering on wires merely as a spacer, and calculate the electric strength of the covering as being that of an equivalent air film. Experiments have clearly shown that this is not the case, and that by paying strict attention to the selection and treatment of the yarns employed, appreciable improvement can be made in electric strength, which is also accompanied by an enormous improvement in insulation resistance. In telephone and similar work this latter improvement is of prime

TABLE 1.

Table Showing Superiority of Cotton Base Papers for High-Temperature Work.

Volts per mil in oil at various temperatures on papers made from various fibres.

Class of paper	Volts per mil at following temperatures:					
	20° C.	40° C.	60° C.	80° C.	100° C.	120° C.
Cotton	780	740	700	660	580	190
Sulphate wood pulp	680	640	590	410	340	—
Hydrated chemical wood	700	660	530	400	—	—
Manilla	700	520	230	180	—	—
Jutes	500	475	430	160	—	—

Note rapid deterioration of jute at 80° C.

TABLE 2.

Tests on Special Pressboards.

Special pressboard made from	Density	Moisture absorption, per cent	Electric strength in volts/mil at		Remarks
			20° C.	90° C.	
Cotton	1·15	95	245	240	Good ageing properties
Wood pulp	1·15	90	220	120	Ages rapidly
Jute and hemp	1·15	125	260	100	Ages rapidly and becomes very brittle

High-class boards, consisting mainly of cotton fibre, should have the following characteristics :—

Density	24 hours' oil absorption, per cent	24 hours' water absorption, per cent	Volts per mil. at 90° C. in air	Remarks
Approximately 0·9..	30	150	240	Soft board for oil immersion
Approximately 1·15	20	100	260	Suitable for slot liners
Approximately 1·3..	2	70–90	300	For h.t. oil-immersed work

importance. The authors have recently devoted considerable attention to this problem, and the following details of the work accomplished may be of interest.

The investigation commenced with a study of the botanical nature of the chemical composition of cotton fibres, bearing in mind the fact that the fibres as applied to insulated wires are, generally speaking, in exactly the same state as they left the cotton plant, since in the processes associated with the production of yarn they do not pass through any chemical or wet process which might remove their natural wax or other impurities. A preliminary survey brought to light the work of Lister,* who carefully analysed the wax and the soluble impurities in cotton, and pointed out that some of the latter are extremely hygroscopic, even up to 32 per cent of their own weight. Matthews, in his book on *Textile Fibres*, suggests that the hygroscopic nature of the untreated cotton fibre (approx. 7 to 8 per cent) is probably due to this constituent. As electrical characteristics usually largely depend on the amount of moisture present, it was decided to dissolve out the impurities present, using various solvents for the preparation, and then make electrical tests. The test-results shown on specimens of specially prepared unbleached cloth treated in various ways have clearly indicated the improvement procurable, although they are so far insufficiently conclusive to establish the exact nature of the process to be employed. It would appear, however, that a treatment of the cotton yarns and fabrics for a short period in a very weak solution (approximately 0·5 per cent) of caustic soda followed by washing is all that is required to render a very considerable improvement in the electrical properties of the cotton. Table 3 shows the results obtained in the tests made.

In addition to these results, experiments with specially prepared cotton yarns have been carried out, using a subsequent treatment of basic dye and further washing, the results of which are summarized in Table 4. These experiments are consequent upon collaboration upon this subject with the British Cotton Industry Research Association, who have also been engaged upon this development.

In view of the results contained in Tables 3 and 4, it is reasonable to hope that one of the lines along which further industrial research will be directed will be that leading to the commercial application of the improvements indicated above as possible in cotton coverings on wires.

Paper insulation on wires is another comparatively recent development. Paper-insulated wire has much in its favour, particularly for use on high-tension transformer work where immersed in insulating oil, since it can be built up to a considerable thickness very much more readily than the insulation applied in the form of yarn.

For cable work also, paper insulation has definitely established itself and development is now proceeding on the lines of improved treatment of the paper to produce dielectrics commercially for the high voltages now being employed.

Enamel-insulated wires are growing in favour on all classes of work. In the past, enamel insulation was largely confined to small wires, and the present B.E.S.A. Specification No. 156 only covers wires up to 0·048 in. diameter. Enamel insulation, when properly carried out, is exceedingly good, and the main difficulty at the moment is that the demand apparently exceeds the supply of good wire, with the result that some very inferior wire is being placed upon the British market.

Asbestos as a wire covering should properly be regarded as a class B material, but for the purpose of convenience will be dealt with here. Asbestos coverings present themselves in three distinct forms, of which the oldest is that in which the asbestos is applied as a paper tape lapped on to the wire and protected with a single cotton covering. This product has been in use for many years on traction work, but more recently the practice has been growing of using wire in which the asbestos is applied to the wire in a wet pulp form, "felted on" and afterwards smoothed over by specially constructed irons. This second class of asbestos-covered wire gives extremely satisfactory results, as it is much more readily bent to coil shapes, etc., without damaging the insulation. A third form of applying the asbestos is in the form of yarn, but this procedure is not common, except as an outside braiding on certain cables which have to pass a flame-proof test, on flexible heater cables and similar work. The serious disadvantages of asbestos are its capacity for taking up moisture and its liability to contain conducting fibres of magnetite. There is hope that both these shortcomings may be largely remedied in the future, in the first case by adopting a suitable water-resisting size, and in the second case by a treatment along the lines of the oxalic acid treatment, details of which were originally published in British Patent No. 24259/1911.

(4) *Varnished-paper products.*—Under the heading of varnished-paper products the various shellac-paper and bakelite-paper materials may be included, together with a limited number of materials in which bitumastic varnishes are employed as binders.

Boards and tubes of the bakelite-paper class are a development of the past 10 or 12 years as far as this country is concerned, and at the moment there is probably no insulating material which causes its producers so much anxiety in manufacture as this particular one. When carefully made by properly and scientifically controlled processes, bakelite-paper products constitute an extremely good Class A insulation and possess the advantage over shellac-paper products that they may be raised to temperatures over 100° C. without appreciable deterioration or softening. The popular idea that bakelite-paper products may be used at temperatures up to 160° C.–180° C. without deterioration is erroneous. The paper constituent loses its nature at temperatures of 100° C. to 120° C., depending on the raw fibre from which the paper is made. Bakelite asbestos, however, may safely be used up to 150° C. without its strength being impaired.

In many quarters bakelite products have earned for themselves severe criticism. In the authors' view this is, however, largely due to the number of pro-

* *Journal of the Society of Chemical Industry*, vol. 21, p. 388.

TABLE 3.

Results of Various Treatments on Unbleached Cotton Cloth.

Treatment to which cotton had been exposed	Insulation resistance in megohms after 20 hours' exposure to 70 per cent humidity at 20 deg. C.	Electric strength (5-second value) in volts per mil.			Tensile strength, in lb./sq. inch		Water absorption, per cent
		After 20 hours' drying at 110° C. tested immediately	After 20 hours' drying at 110° C. tested after 2¼ hours, humidity 70 per cent	After 18 hours at 90 per cent humidity at 19·3° C.	Warp	Weft	
As received	34	95·1	74·1	70·5	45·6	33·5	7·83
After boiling in :—							
Water	1 000	94·0	87·0	74·5	35·4	9·70	9·70
Hot NaOH 3 per cent	490	83·4	77·5	72·0	—	—	8·80
Hot NaOH 2 per cent	572	99·0	79·0	78·0	—	—	9·50
Hot NaOH 1 per cent	676	103·0	83·4	74·1	39·8	29·7	9·03
Hot NaOH 0·5 per cent	1 000	109·0	84	—	—	—	—
Hot NaOH 0·2 per cent	1 000	111·0	83	—	—	—	—
Hot soapy water	228	99·7	85	75	42·8	31·9	11·5
Hot alcohol	290	95·5	73·8	69·2	—	—	8·53
Hot toluene	82	94·8	73	70·5	—	—	7·87
Hot petroleum ether	76	100·5	72	71	—	—	9·0
Hot benzole..	69	101·8	73	70·5	—	—	8·57
Hot petrol	61	98·2	72·8	76·2	—	—	8·8
Hot benzole, followed by alcohol..	132	98·2	71	70·6	—	—	8·95

Note.—It is to be noted that the highest values of insulation resistance and electric strength in the above table are obtained by treatment with weak caustic soda solution.

TABLE 4.

Specially Prepared Cotton Yarns.

Sample	Insulation resistance normal condition (20° C.)	Electric strength in volts per mil, normal condition (20° C.)	Absorption of moisture, per cent
As received	29 megohms	74	5·72
0·5 per cent caustic soda	52 megohms	73·5	5·45
Boiling water	Infinity	87·5	5·6
Water at 26° C.	Nearly infinity	82·5	5·45

Note.—The above treatments were applied for two hours, after which the specimens were washed in cold water and dried.

Further Results indicating Improvement in Insulation Resistance after Basic Dye Treatment.

Sample	Normal condition (20° C.). Sample 38 mils thick	Dry condition (90° C.). Sample 48 mils thick	Damp condition. 90 per cent humidity for 24 hours (20° C.). Sample 60 mils thick
As received..	25 megohms	Infinity	3·4 megohms
0·5 per cent caustic solution	1 000 megohms	Infinity	175 megohms
0·5 per cent caustic solution plus basic dye ..	1 200 megohms	Infinity	425 megohms

Note.—The last column shows the improvement maintained under humid conditions after basic dye treatment.

prietary grades of bakelite paper on the market which fall far short of what is required in a first-class insulator. The only serious disadvantage possessed by the better grades of bakelite-paper products is the phenomenon known as "tracking." When a bakelite material has once been under the influence of any form of disruptive discharge, whether it be a power arc or only a flash over the surface during a pressure test, the path followed by the arc becomes a conducting path even at a comparatively low voltage. This is generally referred to as "tracking," and when once started on a bakelite product of any kind is extremely difficult to eradicate. All organic fibrous materials naturally char in the presence of an arc, but there is an enormous difference in the extent of the damage done. The figure shows specimens of (1) bakelite-paper board, (2) shellac-paper board, (3) hard pressboard, (4) linseed-oil-impregnated wood, (5) micanite, and (6) vulcanized fibre, all of which have been subjected to the E.R.A. standard fuse-wire test as described in their publication A/S9. The number of times the test was made before the photograph was taken is marked below each sample.

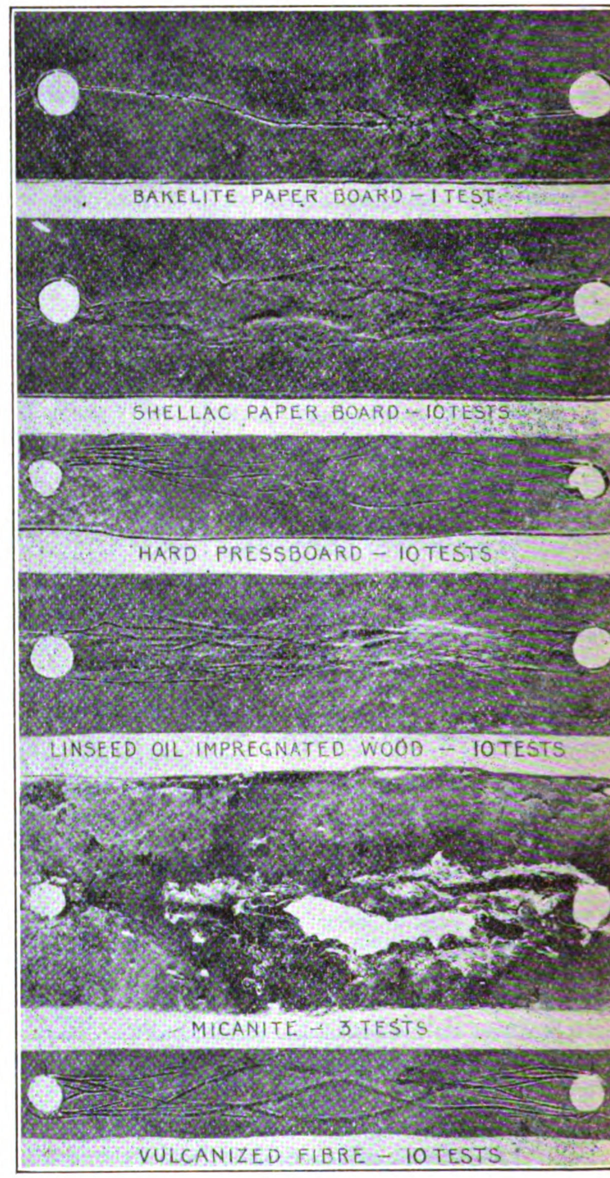
Under this test bakelite-paper materials, unless protected by special varnishes, almost all invariably failed on the first application of the test, whereas all other fibrous insulating boards withstood from 6 to 20 applications before failure. Vulcanized fibre shows up singularly well in this connection, proving its suitability for use as a fuse carrier. It has been pointed out by Moureu and Dufraisse * that the presence of small quantities of antioxygenes (as, for instance, hydroquinone) prevents auto-oxidation in substances of the phenol and aldehyde groups. Experiments made with bakelite resins which contain traces of hydroquinone have shown a marked improvement with regard to the tracking defect previously referred to.

Possibly the development and application of this discovery, or the adoption of special protective varnish films with which considerable improvement has been obtained, will remove one of the most serious shortcomings in an otherwise extremely useful material.

Shellac-paper products are limited in their use by their tendency to soften at temperatures above 80° C. unless subjected to an extended "curing" treatment. One development in electrical manufacture, however, has been the application of shellac-treated paper to the manufacture of condenser terminals. It is this development which has done much to render possible the manufacture of electrical plant for transmission line pressures up to 220 000 volts, and terminals have already been produced capable of dealing with one million volts. It may be interesting to note that the dimensions of such terminals are in the neighbourhood of 42 in. diameter and of 20 ft. length. A certain tendency has developed to blend shellac and synthetic varnishes with the object of obtaining the better characteristics of both in the finished product. In the authors' opinion, however, the risks of accentuating some of the bad characteristics in either constituent render this practice a doubtful one.

The bitumen-paper group of materials possesses distinct advantages on low-temperature apparatus, due to the extremely high electric strength and water-resisting properties of good-grade bitumens. The use of such materials, however, is very limited, due to their low softening points, although this is frequently counteracted by an outer reinforcing layer of bakelite-paper material.

* *Comptes Rendus*, 1922, vol. 174, p. 258.



Results of E.R.A. fuse-wire tests.

The processes involved in the production of varnished-paper products are amongst the most highly technical which an insulation engineer is called upon to contend with, and call for the closest possible scientific control and technical supervision.

(5) *Vulcanized fibre.*—Vulcanized fibre is shown by laboratory tests to be one of the poorest insulating materials in modern use, but nevertheless it has given

most excellent results for many years in a varied number of applications, including rail-joint insulation, fuse holders, slot wedges, packing and spacing blocks, contact carriers on low-tension switches, etc.

Unfortunately, post-war supplies of vulcanized fibre have not been comparable with the high-quality product available 10 years ago. The general acceptance of vulcanized fibre as a second-grade insulator only, and its disuse as primary insulation on anything but the lowest-voltage work is the most marked advance which has been made in the industry with respect to this material. It might be mentioned here that the V.D.E. rules have definitely specified that vulcanized fibre shall not be used in positions where the voltage across the material exceeds 15 volts per mil. A recommendation of a similar nature has been put forward by the E.R.A. limiting the stress to 20 volts per mil in dry situations. Leatheroid, which is classified as a grade of vulcanized fibre, affords an excellent material for slot-lining purposes, but in many instances is now being replaced by tough flexible pressboards, since the latter possess better ageing characteristics.

(*b*) I.E.C. Class B Materials.

(1) *Mica products.*—The effect of temperatures, within the range met in electrical machines, on Class B insulation is a question which is capable of considerable discussion and should probably be the subject of considerable further investigation before any very definite conclusions can be arrived at. Mica itself does not begin to disintegrate until raised to temperatures well in excess of those encountered in electrical plant, but the bonds used in building it up into micanite, and also the paper and fabric "carriers" which are frequently employed as a backing for mica, are in most cases affected by temperatures in the neighbourhood of 100° C. The I.E.C. rules permit Class B insulation to contain Class A material for structural purposes only and specify that only where such material may be destroyed without impairing the insulating or mechanical qualities of the combined material may the latter be considered as Class B insulation. There seems to be some considerable latitude in interpreting this rule, and it might be suggested here that in a future revision of the B.E.S.A. Specification some definite values should be specified as a minimum for the percentage by volume of truly fireproof material (as, for instance, mica, asbestos, etc.) that a Class B insulation should contain. Micafolium wraps not infrequently contain only 25 per cent of mica by volume—figures as low as 14 per cent by volume have been found in wraps made by certain foreign manufacturers—and yet such a wrap is frequently looked upon as a Class B insulation. For large machine work a figure in the neighbourhood of 35 to 40 per cent of mica by volume in mica-wrapped insulation would probably be a reasonable figure for a Class B insulation.

In setting the above figure, it might here be pointed out that much misunderstanding has frequently been caused by the use of percentage-of-mica figures based on weight and not on volume; such figures are of course very much higher and quite misleading. When expressing percentage-of-mica figures in mica wraps on, for instance, alternator bars, figures by volume higher than 45 per cent are almost unobtainable commercially, but such figures expressed as a percentage by weight may be 65 to 75 per cent of mica, depending on the specific gravities of the paper and bond employed. In micanite plate (in which no fibrous material is employed as a "carrier") it is not difficult to obtain percentages of mica by volume of 85 per cent.

The selection of splittings used in building up mica products also requires more close attention, particularly on high-voltage work. It is to be regretted that at the moment the electrical manufacturer is so hopelessly in the hands of brokers in selecting splittings, and there is no definite specification for the purchase of this important material. Brokers' grade numbers vary enormously, and of recent years certain large consumers have found it necessary to abandon the use of grade numbers entirely and employ suitable standard grade names. Splittings are then bought to blue-print drawings, depicting the size and thickness of the flakes in an average handful of the material to be supplied. This arrangement has worked extremely satisfactorily and has eliminated a very considerable amount of confusion.

The bond used in built-up mica insulation constitutes, as already stated, the weakest part. Shellac, when carefully selected and free from rosin and other impurities, yields to treatment which renders it an excellent bond, but calls for the strictest observance of technical detail in carrying out the processes where it is employed. Improper treatment or impurities in the bond may easily produce volatile matter at the high temperatures met with in machines, with deleterious results.

Among the more recent improvements introduced into the building of mica products, the use of machine building in place of hand building should be mentioned. The authors' experience is that machine-built micanite is mechanically and electrically superior to that built by hand, even when lower grades of raw splittings are employed in the machine-built material. Machine-built micanite is naturally cheaper to manufacture. Another important development has been the general introduction of what is known as "cushion pressing," i.e. placing a resilient material such as thin felt or heavy cloth between the sheets of micanite whilst being pressed. This results in an even distribution of bond and mica and produces beautifully uniform sheets, free from the light patches familiar in micanite made between solid metal platens.

The synthetic resin group of varnishes lend themselves to certain classes of work in connection with Class B insulation, but not as a rule in conjunction with mica wraps, since they cannot be successfully dealt with in the ordinary Haefely wrapping machine. They also possess the disadvantage that when dry they are exceedingly brittle. In any case their use is not advisable in any position where a disruptive discharge is liable to occur. In conjunction with asbestos fabrics, however, they are used to produce a laminated board which is essentially a Class B material and is extensively used for packing blocks where high temperatures and heavy mechanical stresses are encountered.

(2) *Asbestos products.*—Asbestos products enter the field of insulating materials in several forms. As a covering for wires and as a base for varnished fabric boards, asbestos has already been referred to.

In the form of paper, asbestos is extensively used as an insulation between turns in strap windings. Unfortunately, asbestos papers are generally weak mechanically, and the special treatments so far applied to improve electric strength (as, for instance, the oxalic acid treatment) by removing the magnetite fibres from the asbestos tend still further to reduce the mechanical strength of the material. It is to be feared that the raw fibre used in paper making is too frequently residue material and contains many impurities. Probably the use of high-quality spinning fibres would go far to remedy this defect without greatly increasing the cost.

Asbestos tapes are becoming more extensively used than previously in place of cotton tape in coil insulation which is called upon to meet a Class B specification. The chief disadvantage of using such tape at present is the difficulty in securing thin tape. The majority of tapes on the market at anything like a reasonable price, vary in average thickness from 12 to 20 mils. The difficulty in making a thinner tape is entirely in the production of fine asbestos yarns without the introduction of cotton. There seems little doubt that if manufacturers' specifications would permit a comparatively small percentage of cotton (e.g. 10 or 15 per cent) to be included with the asbestos, these tapes could be produced down to average thicknesses of 7 to 8 mils. For the majority of work it is probably permissible to regard an asbestos tape with 15 per cent of cotton in its structure as coming within the limits of a Class B specification.

The various asbestos arc-shield materials are, it is suggested, classifiable under the heading of Class B insulation. The E.R.A. have recently subdivided these materials into a number of classes, and their classification is followed in Appendix 1. All the materials of this kind which the authors have had the opportunity of examining—some 54 in all—fall far short of the ideal, and particularly with regard to the requirements necessary for high-tension direct-current traction work. It is questionable how far asbestos itself constitutes an ideal filler for a high-tension arc-resisting material, except when added in small quantities as a mechanical reinforcement. It is probable that an arc-resisting material with a low-melting-point (500° C.–600° C.) vitreous binder, and employing powdered mica, asbestos, pumice or chalk as a filler may supply the want now badly felt. At least one such material has been produced experimentally and has proved most promising.

(c) I.E.C. Class C Materials.

The I.E.C. rules define Class C materials as fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.

(1) *Block mica.*—Block mica finds considerable use in the electric heater industry and is to a certain extent still employed on high-class commutator work, but by reason of its high cost it is replaced wherever practicable by micanite.

(2) *Porcelain.*—With the increase of high-tension work, porcelain is becoming the centre of much attention, and extensive research work is now in hand with a view to improving this material both on the Continent and in the United States. British manufacturers do not seem to have devoted the same attention to the scientific development of electrical porcelain, involving, as it does, a complete study of the clays utilized, grain size, blending, and of the problems of close temperature control during firing. Porcelain and pottery making is one of the oldest industries for which Great Britain is famous, and it is to be hoped that the conservative attitude of those in charge of this particular industry will not exclude British products from the high-grade electrical porcelain market of the future.

(d) Materials Unclassified by the I.E.C. Rules.

(1) *Varnishes.*—The manufacture of high-grade insulating varnishes in this country has made very definite progress of recent years. The main efforts of most varnish makers have been directed towards reproducing the original varnishes which were introduced into this country, largely from America, when the electrical industry was enjoying its first boom. Electrical manufacturers also have closely followed the practice of earlier days in the use of these materials. In Appendix 4 a general classification of insulating varnishes in use is embodied. Probably by far the most important of the classes of varnish named are those with a linseed oil base, which constitute the bulk of insulating varnishes at present in use for dipping and impregnating purposes.

The development of outdoor apparatus, particularly in connection with outdoor substation work, has called for special insulating varnishes, capable of protecting organic insulation against extreme weather conditions. No generally accepted practice in this connection is evident at the moment. In considering this problem, however, the figures given in Table 5 are of general interest as indicating the relative protecting power of various classes of varnish.

(2) *Moulded compositions.*—Moulded compositions are a form of insulation the value of which is becoming more appreciated as the art of making mouldings becomes better understood. The most formidable difficulty in this class of work is that of producing moulds at a reasonable cost. The classification in Appendix 3 indicates the general subdivisions into which insulation of this kind can be classified. Of these, the synthetic resin group of moulded products have certainly come as a boon to engineers, since they are capable of retaining their form and strength at temperatures where rubber and bitumen mouldings soften. The use of synthetic resin mouldings for magneto work, small distributors, commutators and similar parts is now quite general. Here again, however, the danger of " tracking " must be taken into account in introducing these materials into electrical designs.

Mouldings with a rubber base are chiefly applicable to high-grade instrument work and radio specialities.

The bitumen class of mouldings is probably more in general use than any other, as it includes a very large number of products, such as switch handles, terminal blocks, cable-rack insulators, etc., all of which can be made from a very cheap grade of raw materials, particularly as the fillers employed may readily be prepared from factory waste.

Casein forms the binding base of another group of moulded materials which, although comparatively little used in this country, is becoming considerably more widely used on the Continent of Europe. One of the most striking features of the recent Trades Exhibition in Vienna was the number of products of this type exhibited. Galolith is one example of this type of material.

Amongst other materials which may be regarded as moulded materials are a group of cold-moulded products, using cement, lime and other natural clays as binders. The majority of these materials are particularly applied for arc shields and similar work, and bear a close relation to the asbestos arc-resisting boards already referred to.

TABLE 5.

Protective Powers of Various Varnishes against Penetration of Moisture.

Varnish	Number of coats	Moisture absorption, per cent
Untreated sample	0	145
Black finishing varnish ..	1	104·3
Black finishing varnish ..	2	94·0
Bitumastic varnish.. ..	1	20·09
Bitumastic varnish.. ..	2	1·12
Clear baking varnish ..	1	100·5
Clear baking varnish ..	2	42·82
Clear baking varnish ..	3	1·19
Clear baking varnish ..	4	0·94
Clear baking varnish ..	5	0·42
Bakelite varnish	1	101·3
Bakelite varnish	2	95·3
Grey insulating varnish ..	1	114·9
Grey insulating varnish ..	2	93·42

(3) *Insulating oils.*—The use of insulating oils has increased enormously of recent years with the rapid growth of transformer and high-tension switchgear work.

In pre-war days a large amount of Russian oil was used in Great Britain, since this class of oil is singularly free from sludge, being what is known as a bitumen-base oil. The complete cessation of supplies from Russia, which lasted until a few months ago, caused the transformer builders to depend on America for their supplies. Unfortunately American oils are petroleum-base oils, and unless very carefully refined and produced have a serious tendency to sludge. The difficulties encountered with sludging became so real that electrical manufacturers have been compelled to spend very large sums of money in endeavouring to perfect methods of testing for sludge. The B.E.S.A. Specification 148 outlines the test, devised by Dr. Michie, which is at present recognized as a standard test. This test is unquestionably good, but apart from the fact that it takes extremely careful handling to obtain consistent results, it takes 48 hours to complete. Such a long period is frequently extremely inconvenient in actual practice, and to obviate this difficulty a very simple and apparently reliable method has recently been suggested by Mr. W. H. Nuttall.* This short test depends in principle on the fact that oils containing large amounts of unsaturated hydrocarbons (and therefore having a strong tendency to sludge) exhibit a very much stronger interfacial tension towards water than that shown by oils which contain no unsaturated hydrocarbons. This is due to the enormous affinity that unsaturated hydrocarbons have for water. The test consists of allowing a known quantity of oil to rise in bubbles through distilled water from a standard small orifice. The drops are expelled from the orifices under a definite head of oil. Oils which contain a large amount of unsaturated hydrocarbons will rise through the water in small bubbles, whereas the good non-sludging oils rise in large bubbles. The number of bubbles per unit volume of oil is claimed to afford a direct measure of the sludging properties of the latter. The various properties of insulating oils commonly in use are set forth in Appendix 5.

With reference to the electric strength, it may be pointed out that although B.E.S.A. Specification 148 definitely lays down that the electrodes should be horizontally arranged, recent research has quite definitely established that with oils of the purity referred to in that specification, where all other conditions are equal, the question as to whether a horizontal or a vertical arrangement is employed affects the test results to an absolutely negligible extent.

(4) *Bituminous materials.*—It is probably not generally realized what a large number of different materials are available under the heading of bitumens, using the word in its widest chemical sense. Appendix 6 is intended to convey some indication of the wide field covered by this group, showing electrical properties where they apply. Many of the materials possess extremely satisfactory electrical characteristics, whereas others are far from satisfactory. There is little doubt that the practice of regarding materials which have a black bituminous appearance as bitumen has resulted in much trouble to electrical engineers in the past.

For impregnating work and as a filling for high-tension apparatus the quality of the bitumen employed has to be very carefully checked, particularly with regard to electrical characteristics and to the so-called "dropping point." Unfortunately there is no standard specification for this material. In view of the importance which is undoubtedly attachable to this group of materials, it is suggested here that the tests, of which the results are given in Appendix 6, might be regarded by users as effecting a satisfactory criterion to cover purchasing requirements. These tests should cover electric strength, dropping point, shrinkage, ash content, and nature of fracture. The dropping-point test is best carried out either in accordance with the ball and ring method specified by the American Society

* *World Power*, 1924, vol. 2, p. 92.

for Testing Materials in their Specification No. D36–21, or by the Kramer-Sarnow mercury-globule method. The electric tests are conducted in accordance with the rules laid down in the previously mentioned A/S2 document of the E.R.A., on sheets of bitumen prepared under pressure between amalgamated brass platens. Whilst pressing out into a sheet, the material should be at a temperature not more than 10 degrees below its dropping point. The whole field covered by these materials is now being investigated by the E.R.A.

One material which is singularly interesting is vulcanized bitumen. This material has the appearance and general characteristics of rubber, and yet is absolutely unaffected by continued exposure to hot transformer oil. Cable manufacturers have utilized vulcanized bitumen for some years, but its use in other classes of electrical apparatus does not appear to have been adopted to any extent.

(5) *Rubber and gutta-percha products.*—Rubber and gutta-percha are probably the oldest commercial dielectrics, and although used extensively in the cable industry and also in the manufacture of ebonite and similar materials for the manufacture of scientific instruments, telegraph apparatus, radio equipment, etc., are not used to any great extent in heavy machine work. No appreciable developments are noticeable in recent years, except the efforts which have been made to produce an oil-resisting rubber. Experiments have been made with rubber in the form of rubber latex with the idea of improving papers and pressboards, but for electrical work there is nothing in its use to recommend it, since the paper in which it is incorporated unquestionably ages rapidly at temperatures exceeding 80° C. Gutta-percha—found so satisfactory in early cable work—is not used extensively in the industry as a whole at the present time.

5. Improvements in Processes of Application of Insulating Materials.

Since all insulating materials are admittedly the weakest point both electrically and mechanically in any piece of well-designed electrical plant, it has been necessary to compensate as far as possible for their inherent weaknesses by improving the processes included in their application. The past four years have witnessed considerable progress in the improvement of insulating processes employed in manufacturing electrical machinery. This work has ceased to be a series of rule-of-thumb operations, but in the majority of large factories is carried out to definite specifications prepared under highly trained technical supervision and employing up-to-date scientific methods for controlling and recording temperatures, pressures, specific gravities of liquids, etc.

These improvements fall generally under the following headings :—

(*a*) Improvements in machinery.
(*b*) Improvements in processes resulting from better knowledge of the properties of various materials.
(*c*) Technical control of processes—process specifications.
(*d*) Training of specialized operatives.

(*a*) Improvements in Machinery.
(*b*) Improvements in Processes resulting from Better Knowledge of the Properties of Various Materials.

These two subjects are so closely allied that they will be dealt with together in relationship to the use of the various materials already mentioned in Part 4 of the paper. It may be pointed out here that such improvements in processes as are specifically applicable to the manufacture of materials dealt with in the earlier part of the paper have been already considered in dealing with the materials themselves. The following paragraphs cover the application of the various materials to finished electrical machinery. Generally speaking, manufacturers have at last appreciated that the majority of insulating processes are specialized operations requiring suitably designed machinery, and that the struggle to perform these difficult operations with machine tools constructed for other purposes very seldom pays in the long run. The number of firms now specializing in the manufacture of machinery for insulation work bears ample testimony to the truth of this latter assertion.

In connection with cell-insulating methods, the controversy as to the best form of insulation for long bar conductors in high-speed generating plant still continues, although the practice of inserting micanite tubes in the machine slots and afterwards drawing in the conductors and wedging them into position appears to have been abandoned in long-slot machines by those who advocated it. The use of soft cells in which varnished cloth was used has also not found favour recently.

Modern practice is divided between :—

The use of mica-silk tape applied by hand throughout on both slot portions and end windings.

Machine-wrapped bars (usually known as the Haefely wrap) in which micafolium is used on the slot portion and the end connections taped with mica fabric tape, etc.

Green cell insulated bars in which wet mica cells built on fine jap paper are applied by hand.

In all these cases the bars are pressed to shape after insulating. There has not been much improvement to record in these processes of recent years except in regard to the more careful selection of the materials used and the improvements effected in pressing dealt with later.

Coil insulation.—The chief changes in the insulation of armature and field coils have been brought about by the frequent use of square and rectangular conductors. In many cases bare conductors are now bent and formed to shape and the insulation afterwards inserted between conductors in the form of micanite, treated paper, pressboard, treated asbestos, etc. The coil is then served with special enamels and insulated with plain or mica-fabric tapes. This practice requires much greater skill and attention to the processes and materials employed than did coil formation with the d.c.c. wires of former days, but has the advantage of an

improved space factor. These remarks are equally applicable to transformer coils.

In small apparatus coils it is of interest to note the automatic machinery recently introduced for winding small coils. The Leesona coil winder may be taken as typical of this class. Such machines in proper hands can put up wonderful output records but need skill in operation and must be fed with very carefully selected raw materials.

Pressing.—Under this heading several distinct modern advantages may be mentioned.

The use of hydraulic presses is considered the best practice for pressing mica plate, built-up varnish-paper products of all kinds, and similar work where it is essential that the platen shall be at a temperature of 100° C. to 150° C. Such presses have been greatly improved of recent years and the general adoption of the drilled steel platen in place of the more cumbrous cast-iron platen has resulted in an increased press capacity both because more platens can be inserted in the limited "daylight" of the press and because the small amount of metal in the platens allows more rapid heating and cooling. Presses of this type are also equipped with cold-water cooling direct from a water supply.

For commutator **V**-ring work, heavy moulded composition parts, etc., presses are used with no heated platen, but in this case special provision is made to heat and water-cool the moulds themselves. The adoption of this practice has greatly increased the output per press.

The class of press, however, to which most attention has been given is the screw-operated clamp press in general use for steam-pressing long insulated bars and similar work. The design of such presses in order to get quick heating and cooling with no distortion, calls for considerable skill. The object of steam-pressing is to obtain a hard wrap on turbo-bars and such parts to definite dimensions with no soft places, blisters or air-spaces, and it is in the proper selection of materials and careful control of temperature, time and pressure that most improvement has been obtained with these presses. A divergence of opinion exists as to whether insulated bars in these presses should be pressed to size against stops or should be pressed with a definite applied pressure, relying on the correct amount of material having been wrapped on the bars to produce the required size.

Varnish treatment.—Two distinct trends of opinion exist with regard to the correct varnish treatment for electrical machinery and windings. The mere dimensions of the machines of course decide the point as to whether the windings should be varnish-treated before or after assembly. It is quite usual practice to wait until small machine parts are completely wound before treating with varnish. The whole machine is treated in this case, including the iron parts, which are afterwards wiped clean. Parts and coils for large machinery, on the other hand, are of necessity varnish-treated before being inserted into the machines. The point of difference, however, lies in the actual method of varnish treatment, i.e. whether vacuum impregnation or hot dipping results in the best product. Although some authorities still hold a brief for vacuum impregnation it is more generally recognized that hot dipping methods give results at least as good and often better at less cost in time and equipment. One of the most salient disadvantages of vacuum impregnation is the fact that the depth of varnish impregnation entails the use of either a slow-drying varnish in order to prevent the air surface drying too rapidly and preventing the access of air to oxidize the varnish in the interior, or a varnish containing an excess of internal driers. Both these types of varnish tend to release acid compounds which deteriorate the insulation. In the hot dipping process a 24 hours' baking at 120° C. before dipping leaves the insulation extremely dry, and if it is immediately transferred hot to a varnish tank and immersed in varnish until cold, practically all the advantages of a vacuum treatment are obtained.

On removal from the varnish and after draining, the insulation should be transferred back to the oven, as in this case a quicker-drying varnish can be used because, even should the outer film oxidize, the presence of oxygen in the interstices of the material accelerates internal drying. In vacuum treatment, of course, very little, if any, oxygen is present in these interstices. The chief change of practice of recent years to be noted is therefore the falling into disuse of vacuum impregnation.

Baking.—Great improvements have recently been made in baking and drying equipment. The scientific principles of the quick removal of moisture during drying, and quick oxidation of varnish during baking, have been closely studied and the ovens modified accordingly. In many factories the "through" type of oven is in use, ensuring a definite and gradual rise of temperature as the parts pass through on a conveyor until a maximum is reached, followed by a gradual reduction of temperature before removal. Thermostatic control and temperature recorders are almost everywhere employed since engineers have realized how much depends upon a close adherence to times and temperatures in baking insulating materials. Air circulation has been greatly improved in modern oven designs. The futility and, in fact, bad effect of "stewing" varnished products in their own varnish fumes have been realized by all, and the totally enclosed oven is a thing of the past. Electric heating of the air supplied to baking ovens is employed to a limited extent. In certain instances the recovery of the solvents from drying ovens has been considered, but such a scheme is hardly practicable except in specialized factories making one range of products only, from which ovens with a small ratio of total volume to volume occupied by the products being treated can be built.

A special application of baking processes is the so-called bakelization of synthetic resin products. According to the original ideas of treating the products, the final condensation process was carried out by baking at 150° C. in strong steel vessels under 120–160 lb./sq.in. pressure of air. Modern experts practically all agree that such high temperature and high pressure baking is quite unnecessary. With recent phenol-aldehyde varnishes bakelization can be

produced equally well with a prolonged baking of 40 to 60 hours at 115° C. to 120° C., which is a temperature far less likely to do any permanent damage to the organic constituents of the insulation.

Assembling, taping, etc.—In the assembly of insulated parts no appreciable changes can be discerned except perhaps in the special case of insulating parts of rotating machines running at speeds up to 3 000 r.p.m. A particular instance of this is a commutator for such speeds in which micanite insulation is tested to the utmost. Commutator work in general calls for very special treatment, but the methods of checking for truth during building, tightening and seasoning, have not appreciably changed during recent years. Block mica is hardly ever employed in modern commutators and in its place a segment micanite containing only 3 per cent, or at the most 5 per cent, of bond is used. A recent innovation is the checking of all mica parts for thickness under a definite pressure comparable with that met with in the finished commutator.

Finishing.—Finishing has been the subject of much attention of recent years, and the high finish on insulated parts exhibited at Wembley by various specialist firms is an eloquent testimony of the steps that have been made. To secure good finishes, cleanliness and complete absence of dirt and moisture are essential. Many firms have taken the precaution of providing special dust-excluding ventilation, oiled floors, double doors, etc., to their varnish-finishing departments.

Transport and storage.—Probably more insulation failures are due to careless handling and damage in transport than to any other cause. Considerable attention is being given to these details by most manufacturers, and practice has shown that the provision of special bogies and transport facilities usually more than compensates for their initial cost and upkeep.

(*c*) Technical Control of Processes—Process Specifications.

In paragraphs 4(*a*)(4) and 4(*b*)(1) above, specific cases have been cited of the necessity for the strictest control of every detail in the process of insulating modern electrical equipment and plant. So varied are the many stages through which a material passes, depending upon its physical and electrical characteristics and upon the ultimate part it is to play as insulation, that modern practice has developed the use of process specifications which take the form of detail shop instructions covering all essential shop points upon which the successful manipulation of the material may depend. Appendix 7 gives a typical sample of a process specification.

In spite of the fact that operatives are more highly specialized and therefore can be trained in detail operations, these process specifications have been rendered more necessary of late years in this country, partly because modern design has developed the use of a wide range of insulating materials, more nearly as their ultimate electrical properties permit, and partly because there is a greater tendency to develop the use of special machines which may be operated by semiskilled workers rather than to rely upon the dexterity and experience of highly trained workmen.

The contents of process specifications naturally depend upon the type of plant and personnel in dealing with a particular material, and only those variables which fall outside the broad knowledge of the personnel employed need be recorded. In many cases information sheets giving temperatures, times, pressures, speeds, etc., may be hung at a machine, oven or bench.

By means of such specifications or information sheets electrical insulating processes may be more easily and safely checked and controlled. At the same time new methods and materials may be developed outside the manufacturing areas and then introduced to full production with a minimum of manufacturing difficulties.

(*d*) Training of Specialized Operatives.

Modern firms have proved the necessity of adopting a definite scheme of training operatives, including both the manual training of apprentices by means of instructors and the special training of operators on all machines where the technical significance of each operation is of importance. This training is now extended to the personnel for supervising production, inspection, testing and erecting staffs wherever they are in direct contact with insulating materials, as it has been found that the complexity of such materials demands precise knowledge at each stage at which parts may be handled, transported, erected, etc. In addition, modern practice calls for the development and training of specialists qualified to undertake investigational work into shop problems, design features and test-bed methods. The process engineer of to-day is the outcome of the necessity for the closest shop supervision over insulating work and the need for intelligent investigation into shop problems apart from production work. Only by such means can the latest developments in special machines and materials be satisfactorily tried out and applied on a production basis.

In conclusion, the authors' experience is that such improvements in the insulation of electrical machinery as have been effected of recent years, have arisen from experience gained through either deliberate development or the intelligent observation and study of defects. A strong plea is made for the complete classification of insulation materials and methods of testing them, and also for closer co-operation between users and manufacturers of electrical plant so that a study of present-day requirements may lead to developments in method and material and permit of full investigation into service and ageing effects as well as into failures that occur.

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APPENDIX 1.—SOME PROPERTIES OF THE CHIEF INSULATING MATERIALS.

Type of insulation	B.E.S.A. class	Usual thickness	Chief particulars			Remarks
		in.	Tensile strength (lb. per 1 in. width) Warp	Weft		
Untreated cloths :						
Cotton cambric	O	0·003	20	15		Used for a backing for cells and tapes
Unbleached linen	O	0·012	105	100		Used for protecting coils
Duckcloth	O	0·020	100	50		Used for motor armature caps
Sized calico	O	0·005	35	20		Used for insulation between layers
Jap silk	O	0·0015	15	12		Used for silk mica tape
Asbestos	B	0·020	—	—		Used for fire-proofing coils
Treated cloths :			Tearing strength (double tear), oz.	Electric strength, V/mil		
Black empire cloth	A	0·007	14	1 000		Used for slot liners
Yellow empire cloth	A	0·007	14	1 000		Used for slot liners
Empire silk	A	0·005	10	1 000–1 400		Used for coil insulation
Mica cambric	B	0·008	—	—		Used chiefly in the form of tape
Mica empire	B	0·010	—	—		Used for cell and washer work
Untreated tapes :			Tensile strength (lb. per 1 in. width)			
Cotton	O	0·005	43			Used for bonding purposes, and as a carrier for varnish
Linen	O	0·007	60			
Surgical	O	0·012	100			
Webbing	O	0·020	120			
Asbestos paper	B	0·008	8			Used for insulating conductors
Asbestos woven	B	0·015	48			Used for insulating coils
Cable paper	O	0·005	25			Used for paper-insulated wires
Treated tapes :			Tensile strength (lb./1 in. width)	Electric strength at 20° C., V/mil		
Black bias	A	0·007	30	1 000		Used for sealing the ends of coils
Yellow bias	A	0·007	30	1 000		Used as above where greater flexibility is required
Adhesive	A	0·015	45	—		Used for various purposes
Para	A	0·015	—	—		Used for waterproof joints
Rubber	A	0·010	—	—		Used for waterproof joints
Impregnated asbestos	B	0·010	12	—		Generally used between high-temperature windings
Mica silk	B	0·008	—	—		Used for insulation of turbo coils
Mica paper	B	0·006	—	—		Used for insulation of railway armature coils
Asbestos mica	B	0·012	10	—		Used for insulation of resistance units, etc.
Untreated papers :			Warp	Weft		
Kraft	O	0·003	20	11		Used for laminated synthetic boards
Greaseproof	O	0·002	22	12	Usually em-	Used for laminated synthetic boards
Sylphite	O	0·003	25	11	ployed as	Used for laminated synthetic boards
Bank	O	0·003	9	7	carriers of oil	Used between turns of fine wire coils
Rope	O	0·006	30	24	or varnish.	Used for paper mica washers
Jap	O	0·001	7·5	1·5	Thus elec-	Used for paper mica tape
Tissue	O	0·001	4	1	trical value	Used for mica cell manufacture
Core disc	O	0·001	3·5	2	will vary	Used for papering laminations
Asbestos	B	0·007	8·6	6·8		Used for insulating fuse boxes

Continued on pages 452 and 453.

APPENDIX 1, *continued*.—SOME PROPERTIES OF THE CHIEF INSULATING MATERIALS.

Type of insulation	B.E.S.A. class	Usual thickness	Chief particulars		Remarks
Treated papers:		in.			
Synthetic varnished sulphate (Kraft)	A	0·005	These materials may be regarded as a semi-finished product, and therefore no electrical value is given		Used for laminated boards and tubes
Synthetic varnished sulphite (greaseproof)	A	0·004			Used for laminated tubes
Shellac varnished sulphate ..	A	0·004			Used for laminated boards and tubes
Shellac varnished sulphite (greaseproof)	A	0·004			Used for laminated tubes
Shellac varnished cable	A	0·005			Used for h.t. insulators
Synthetic varnished asbestos ..	A	0·010			Used for laminated boards and tubes
Linseed oil impregnated	A	0·015	Electric strength, 200–800 V/mil		Used for washers, etc.
Boards and sheets:			Density	Electric strength at 90° C., in V/mil	
Pressboard: grade A	O	$\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$	1·15	218	Ordinary electrical usage
Pressboard: grade B	O	$\frac{1}{32}$, $\frac{1}{16}$, $\frac{1}{8}$	0·9–1·15	205	Soft and absorbent, used for oil immersion
Pressboard: grade C	A	$\frac{1}{32}$	Impregnated	500	Used for impregnated boards
Pressboard: grade D	O	$\frac{1}{32}$, $\frac{1}{16}$, $\frac{1}{8}$	1·3	255	Extra dense. Low moisture absorption
Pressboard: grade E	O	$\frac{1}{32}$	1·15	230	Used for slot linings
Laminated shellac	A	$\frac{1}{16}$–2	1·33	200 (at 20°)	Terminal boards, etc.
Laminated synthetic	A	$\frac{1}{16}$–$2\frac{1}{2}$	1·33	150 (at 90°)	Terminal boards, etc.
Leatheroid	A	$\frac{1}{64}$, $\frac{1}{32}$	—	—	Slot liners
High-grade fibre	O	$\frac{1}{64}$–2	1·15–1·35	75	Slot wedges, etc.
Asbestos millboard	B	$\frac{1}{16}$ up.	1·17–1·18	—	For embedded iron arc shields
Ordinary asbestos cement	B	$\frac{1}{4}$ up.	1·6–1·9	—	Cubical barriers, etc.
Compressed asbestos cement ..	B	$\frac{1}{4}$ up.	1·9–2·0	—	Fireproof chambers
Arc-resisting asbestos cement ..	B	$\frac{1}{4}$ up.	1·9–2·1	—	Arc shields
Bakelized asbestos board	B	$\frac{1}{4}$ up.	1·4	35–50	High-temperature insulation
Impregnated asbestos board ..	B	$\frac{1}{4}$ up.	1·9–2·1	50	High-temperature insulation
Ebonite	A	To thicknesses as required	1·207	200–350	High dielectric at low temperatures
Micafolium board	B		—	400–500	Insulation washers
Hard micanite (Muscovite) ..	B		—	700–900	Used for commutator segments
Flexible micanite	B		—	600	Used for protecting coils and leads
Bakelized cambric sheet	A		1·36	150 (at 20° C.)	For mechanical and electrical work
Flexible mica sheet	B		—	—	Used for insulating leads, etc.
Tubes and cylinders:					
Shellac paper	A	From $\frac{1}{16}$ wall to thickness as required	1·15–1·35	350 (at 20° C.)	Used for low-temperature work
Bakelite paper	A		1·25–1·35	325	Used for high-temperature work
Asbestos	B		1·17	50	Used for high-temperature work
Pure mica	B		2·3	500	High-stress and high-temperature work

APPENDIX 1, *continued*.—Some Properties of the Chief Insulating Materials.

Type of insulation	B.E.S.A. class	Usual thickness	Chief particulars			Remarks
Tubes and cylinders—continued:		in.	Density		Electric strength at 20° C., in V/mil	
Protected mica	B	From $\frac{1}{16}$	2·0		300	Medium-stress and high-temperature work
Micafolium	B	wall to	1·6		400–500	Low-stress and high-temperature work
Bakelite cambric	A	thickness	1·36		250	Mechanical and electrical work
Fibre	A	as required	1·15–1·35		75	For mechanical reasons only
Rods:			Density		Tensile strength, lb./sq. in.	
Bakelite paper	A	$\frac{1}{8}$ up to $2\frac{1}{2}$	1·3		—	High-tension trip gear
Fibre	A		1·15–1·25		8 000	Low-tension trip gear
Ebonite	A		1·2		4 000	Low-temperature high electrical stress
Bakelized cambric	A		1·36		8 000	Switchgear lifting rods
Moulded compositions:			Density	Approximate softening point, ° C.	Electric strength, in V/mil, at 20° C.	
Rubber base (ebonite)	A	General	1·2	70–90	200–350	Low-loss and low-temperature work
Synthetic base	A	moulding	1·2	100–150	–250	Medium low- and high-temperature work
Casein base	A	work	1·3	70–90	200–300	Low-temperature coloured work
Celluloid base	A		1·6	70–100	300–600	Low-temperature coloured work
Bitumen base	A		—	60–90	50–300	Usually black, cheap mouldings
Portland cement and asbestos ..	B		—	—	5–50	Fireproof work
Fireproof and refractory materials:					Electric strength, V/mil	
Porcelain (wet method)	C	—	—		150–200	High-tension insulators
Porcelain (dry method)	C	—	—		80–120	Medium tension
Marble	C	1 to $2\frac{1}{2}$	—		40–80	Switchgear and switchboards
Slate	C	$\frac{1}{2}$ to 2	—		5–20	Low-voltage switchboards
Heavily spotted green mica ..	C	Thin mica	—		1 100	Not recommended for use
Medium spotted green mica ..	C	splittings	—		1 200	Occasionally used on low-grade work
Medium spotted brown mica ..	C		—		2 000	Suitable for mica cells
Clear ruby mica	C		—		2 250	Suitable for condensers
Clear brown mica	C		—		3 500	Used for moulding micanite
Canadian amber mica	C		—		3 800	Used for commutator segments
Clear white (Muscovite)	C		—		3 000	Used for micanite

APPENDIX 2.

Comparison of Temperature Rating Rules of Various Countries.

[Note.—Unless otherwise indicated all figures are maximum permissible temperature-rises.]

			B.S.S. No. 72			B.S.S. No. 168			B.S.S. No. 173 (Traction motors)			V.D.E. (1923)			I.E.C. (1919)		
			T	R	D	T	R	D	T	R	D	T	R	D	T	R	D
1	Ambient temperature	Normal max. permissible	40	—	—	—	—	—	—	—	—	35	—	—	40	—	—
2	A.C. windings in slots of stators or rotors rated for not over 7 000 volts	Class A	55	55	—	—	—	—	—	—	—	—	60	‡	50	55	—
		Class B	75	75	—	—	—	—	—	—	—	—	80	†	70	75	—
3	A.C. windings in slots of stators or rotors rated for over 7 000 volts	Class A	—	—	—	—	—	—	—	—	—	—	—	—	50	55	—
		Class B	—	—	—	—	—	—	—	—	—	—	80†	—	70	75	—
4	Field windings, stationary or rotating (other than 6 and 7)	Class A	55	—	—	—	—	—	—	—	—	—	60	—	—	55	—
		Class B	75	—	—	—	—	—	—	—	—	—	80†	—	—	75	—
5	Exciter field winding	Class A	—	—	—	—	—	—	—	—	—	80	—	—	—	—	—
		Class B	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
6	Low-resistance field or compensating windings of more than one layer	Class A	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
		Class B	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7	Single-layer field windings with exposed surface	Class A	—	—	—	—	—	—	—	—	—	65	—	—	—	60	—
		Class B	—	—	—	—	—	—	—	—	—	80	—	—	—	80	—
8	Short-circuited windings insulated	Class A	60	—	—	—	—	—	—	—	—	5 deg. C. more than (7)			60	—	—
		Class B	—	—	—	—	—	—	—	—	—				—	—	—
9	Windings of armatures having commutators	Class A	—	—	—	40 not enclosed 50 enclosed			65 continuous 75 one hour			60	—	—	50	55	—
		Class B	—	—	—	—	—	—	80	—	—	80†	—	—	70	75	—
10	Short-circuited windings uninsulated	—	*	—	—	—	—	—	—	—	—	*	—	—	70	—	—
11	Iron core not in contact with windings	Class A	—	—	—	*	—	—	—	—	—	—	—	—	70	70	—
		Class B	—	—	—	—	—	—	—	—	—	*	—	—	—	—	—
12	Iron core in contact with windings	Class A	—	—	—	Same as in (9)			Same as in (9)			Same as for windings			Same as for windings		
		Class B	—	—	—												
13	Commutators	Class A	50	—	—	45 not enclosed 55 enclosed			85 continuous 90 one hour			60	—	—	50	—	—
	Slip-rings	Class B	50	—	—	45	—	—	—	—	—	60	—	—	50	—	—
14	Air-cooled transformer windings	Class A	—	55	—	—	—	—	—	—	—	—	60	—	—	—	—
		Class B	—	75	—	—	—	—	—	—	—	—	80	—	—	—	—
15	Oil-insulated self-cooled transformer windings	Class A	—	55 *	—	—	—	—	—	—	—	—	70	—	—	55	—
16	Oil-insulated water-cooled transformer windings (temp. of water 250 deg. C.)	Class A	—	—	—	—	—	—	—	—	—	—	60	—	—	45	—
17	Transformer oil	50	—	—	—	—	—	—	—	—	—	95 (maximum) 85 (water cooled)			90 (maximum)		
18	Transformer cores	—	Not exceed temp. of oil			—	—	—	—	—	—	—	—	—	55	—	—
19	Bearings	—	—	—	—	—	—	—	—	—	—	45	—	—	40	—	—
20	Windings with unobstructed ventilation (B.E.A.M.A.)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
21	Windings with partially obstructed ventilation (B.E.A.M.A.)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
22	Windings in totally enclosed machines (B.E.A.M.A.)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

T = Measured by thermometer. R = Measured by resistance method.

* Must not reach a temperature liable to raise the temperature of adjacent insulated parts above the temperature specified for these parts.
† The V.D.E. Rules allow 70 deg. C. rise for enamelled wire.

APPENDIX 2—*continued.*

COMPARISON OF TEMPERATURE RATING RULES OF VARIOUS COUNTRIES.

[NOTE.—Unless otherwise indicated all figures are maximum permissible temperature-rises.]

American I.E.E. (1921)			Danish (1923)			Belgian Report No. 7 (1921) (Com. Elec. Belge.)			Japanese (1922)			B.E.A.M.A. (1920)		
T	R	D	T	R	D	T	R	D	T	R	D	T	R	D
40	—	—	35	—	—	40	—	—	40	—	—	35	—	—
50	55	60§	—	60	—	50	55	—	50	55	—	—	—	—
70	75	80§	—	80	—	70	75	—	70	75	—	—	—	—
50	55	60§	—	—	—	50	55	—	50	55	—	—	—	—
70	75	80§	—	80	—	70	75	—	70	75	—	—	—	—
—	55	—	—	60	—	—	55	—	—	—	55	—	—	—
—	75	—	—	80	—	—	75	—	—	—	75	—	—	—
—	—	—	—	80	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	60	—	—	—
—	—	—	—	—	—	—	—	—	—	—	80	—	—	—
—	—	—	65	—	—	—	60	—	—	—	—	—	—	—
—	—	—	80	—	—	—	80	—	—	—	—	—	—	—
—	—	—	—	—	—	60	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	60	—	—	50	55	—	50	55	—	—	—	—
—	75	—	80	—	—	70	75	—	70	75	—	—	—	—
—	—	—	75	—	—	75	—	—	—	—	—	—	—	—
—	—	—	75	—	—	70	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	*	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	55	—	—	50	—	—	*	—	—	55	—	—
—	—	—	55	—	—	50	—	—	*	—	—	55	—	—
—	55	—	—	—	—	—	—	—	—	—	—	50	50	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	55	—	—	—	—	50	55	—	—	—	—	50	50	—
—	55	—	—	—	—	40	45	—	—	—	—	—	—	—
90 (maximum)			55 (if not in contact with air 60)			(Not fixed)			90 (maximum)		—	—	—	—
—	—	—	60	—	—	55	—	—	Same as (17)		—	—	—	—
—	—	—	45	—	—	40	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	40	55 rotat. 60 station	
—	—	—	—	—	—	—	—	—	—	—	—	47	65 shunt	
—	—	—	—	—	—	—	—	—	—	—	—	55	70 shunt	

D = Measured by thermo-couples or similar detectors.

‡ This figure is for impregnated windings. If compound-filled 80 deg. C. is permitted.
§ Only applies to windings with two coils per slot. Windings with single coil per slot 5 deg. C. lower when temperature measured by detector.

OTHER RATINGS.

Norway.

The Norwegian Rules are substantially the same as the V.D.E. (1923) Rules.

Traction motor insulation after 1-hour test must not exceed 70° C. for cotton, 80° C. for paper and 100° C. for class B insulation.

France (*R.G.E., 28th May*, 1921).

The French Rules agree with the I.E.C. Rules, with exceptions :—

1. No limit specified for mica, asbestos, etc.
2. Specify 60 deg. C. rise on soldered joints, and at switch contacts, etc.
3. Following limits are set for composite materials :—
   Bakelite, etc., 200° C. max. temp.
   Ebonite, etc., 60–100° C. max. temp.
   Shellacs and gums, 60–100° C. max. temp.
   Marbles and slates, 100° C. max. temp.

Italy.

The Italian Rules differ from I.E.C. in that :—

1. Temperature allowed on rotating armature and on a.c. windings in slots is 5 deg. C. lower than in the I.E.C. Rules.

Sweden (*Schwedische Technalogen Verein*, 1919).

The Swedish Rules differ from V.D.E. in that :—

1. Ambient temperature = 35° C.
2. Varnish-paper products are allowed to reach 105° C. max. (70 deg. rise).
3. Short-circuited non-insulated windings are allowed to reach 115° C. max. (i.e. 80 deg. rise).
4. On transformer oil, when able to come into contact with air : 50 deg. C. rise. When shut off from air : 60 deg. C. rise.
5. Bearings are allowed 40 deg. C. rise.

Spain and Switzerland.

The V.D.E. Rules are, generally speaking, applicable in Spain and Switzerland.

Russia.

The Russian Rules (1923–4) are based on V.D.E. Rules.

APPENDIX 3.

Sample of Standard Grouping and Terminology of Insulating Materials.

TABLE A.

B.E.S.A. Class A and Class O Materials.

Class A Materials include cotton, silk, paper and similar materials when impregnated or immersed in oil of varnish. They also include enamelled wire.

Class O Materials include cotton, silk, paper and similar materials when unimpregnated, unvarnished, or not used under oil.

	Usual trade name	Recommended standard name
(I) *Fabrics*		
(*a*) Untreated cloths..	Cotton cambric	Cambric
	Unbleached linen	Linen
	Cotton duckcloth	Duckcloth
	Sized calico W7070	Sized calico
	Jap silk	Jap silk
(*b*) Treated cloths ..	Varnished cotton cloth	Black empire cloth
	Varnished cotton cloth	Yellow empire
	Varnished silk	Empire silk
(*c*) Untreated tapes ..	Egyptian cotton tape	Cotton tape
	Linen tape	Linen tape
	Surgical cotton webbing	Surgical tape
	Special linen webbing	Linen webbing
(*d*) Treated tapes ..	Black adhesive tape	Adhesive tape
	Bias-cut varnished cotton tape	Black bias tape
	Bias-cut varnished cotton tape	Yellow bias tape
	Varnished cotton cloth	Empire tape
	Varnished silk cloth	Empire silk tape
(*e*) Untreated sleeving	Glace tubular cotton braiding	Glace sleeving
	Tubular cotton braiding No. 1 white and special	Cotton sleeving
(*f*) Treated sleeving ..	Varnished cotton tubing	Empire tubing
	Varnished silk tubing	Empire silk tubing
(*g*) Untreated cords ..	Manilla rope	Manilla cord
	Loom twine	Loom twine
	Gilling's twine	Gilling's twine
	Cotton braiding	Cotton braiding
	Finishing twine	Finishing twine
	Barbour's No. 3 twine	Shoe thread
	Sea Island yarn	Cotton yarn
(*h*) Treated cords ..	Gilling's treated twine	Gilling's treated twine
(II) *Papers*		
(*a*) Untreated papers	Red rope paper	Rope paper
	Strong soda woodpulp wrapping paper	Kraft paper
	Hydrated chemical woodpulp greaseproof paper	Greaseproof paper
	Machine glazed sulphite woodpulp paper	M.G. sulphite paper
	Sulphite woodpulp unsized cable paper	Cable paper
	Bond paper	Bond paper
	Pure Japanese tissue paper	Jap paper
	Tissue paper	Tissue paper
	Core-disc paper	Core plate paper
	Homogeneous typing paper	Bank paper
(*b*) Treated papers ..	Shellac treated bear paper	Shellac kraft paper
	Shellac treated gramme paper	Shellac greaseproof paper
	Synthetic varnish treated bear paper	Bakelite-kraft paper
	Synthetic varnish treated gramme paper	Bakelite-greaseproof paper
	Shellac treated sulphate woodpulp cable paper	Shellac cable paper

TABLE A (*continued*).

	Usual trade name	Recommended standard name
(III) *Boards, rods, tubes and cylinders*		
(*a*) Boards	Flexible pressboard	Flexible pressboard
	Presspaper (on rolls)	Presspaper
	Soft pressboard	Grey pressboard
	Dense pressboard	Dense pressboard
	Ordinary pressboard	Ordinary pressboard
	Shellac paper board	Shellac paper board
	Synthetic varnish paper board	Bakelite paper board
	Fibre boards	H.Q. fibre
	Leatheroid (and leather paper)	Leatheroid
(*b*) Tubes and cylinders	Shellac paper tubes	Shellac paper tubes
	Shellac paper cylinders	Shellac paper cylinders
	Synthetic varnish paper tubes	Bakelite paper tubes
	Synthetic varnish paper cylinders	Bakelite paper cylinders
	H.Q. fibre tube	H.Q. fibre tube
(*c*) Rods	Synthetic varnish paper rod	Bakelite paper rod
	H.Q. fibre rod	H.Q. fibre rod
(IV) *Moulded composition and rubber*		
(*a*) Boards	Ebonite	Ebonite
(*b*) Tubes	Ebonite tube	Ebonite tube
	Soft rubber tube	Soft rubber tube
(*c*) Rods	Ebonite rod	Ebonite rod
	Soft rubber cord	Soft rubber cord
(*d*) Sheets (i.e. flexible —distinct from " Boards")	Thick rubber sheet	Rubber
	Oil-resisting synthetic rubber	Oil-resisting rubber
	Cork composition	Cork composition
(*e*) Tapes	Type " N " rubber tape	Admiralty rubber tape
	Para rubber tape	Para tape
(*f*) Special mouldings	Ordinary arc-resisting moulded composition parts	Ord. arc-resisting mould
	Special arc-resisting moulded composition parts	Special arc-resisting mould
	Standard-grade moulded composition parts	Ord. grade mould
	High-grade synthetic resin arc-resisting moulded composition parts	Special bakelite mould
	High-grade synthetic rubber arc-resisting moulded composition parts	Special ebonite mould
(V) *Varnishes, oils, etc.* (*not including insulating oils*)		
(*a*) Insulating varnishes	Shellac (0·975) varnish	Shellac varnish (0·975)
	Lacwatt No. 49 varnish	Lacwatt No. 49
	Grey insulating varnish	Grey insulating varnish
	Thinner for grey insulating varnish	Thinner for grey insulating varnish
	Synthetic insulating varnish	American bakelite varnish
	Synthetic insulating varnish	Formite (bakelite) varnish
	Baking coil varnish	Baking coil varnish
	Baking cloth varnish	Baking cloth varnish
	Flexible black baking varnish	Flexible black baking varnish
	Black finishing varnish	Black finish varnish
	Flexible mica sticking varnish	Flexible mica sticking varnish
	Glossy air-drying varnish for meter coils	Air-drying coil varnish
	Hard-drying copal varnish	Copal varnish
(*b*) Gums, etc. ..	Hydrolene gum, grade " B "	Impregnating bitumen
	Special elastic bitumen, grade " G "	Special elastic bitumen
	Texacto No. 130 filling compound	Cond. terminal compound
	Paraffin wax	Paraffin wax
	Sticking compound	Chatterton compound
	Resin	Resin
	Manilla gum	Manilla copal gum

Continued on page 458.

TABLE A (*continued*).

	Usual trade name	Recommended standard name
(V) *Varnishes, oils, etc.* (*not including insulating oils*)—*continued*		
(*c*) Oils, etc.	Raw linseed oil	Raw linseed oil
	Boiled linseed oil	Boiled linseed oil
	Double-boiled linseed oil	Double-boiled linseed oil
	Thin fluxing oil for hydrolene gum	Thin flux oil
	Methylated spirits	Methylated spirit
	Genuine American turpentine	Genuine American turps
	South American turpentine	South American turps
	Turpentine substitute	Turps substitute
	Venice turpentine	Venice turps
	Castor oil	Castor oil

TABLE B.

B.E.S.A. CLASS B MATERIALS.

Mica, asbestos, and other materials capable of resisting high temperatures. If Class A material is used in conjunction with Class B material for structural purposes only and may be destroyed without impairing the insulating or mechanical qualities of the combined material, then the material may be considered as Class B.

	Usual trade name	Recommended standard name
(I) *Mica products*		
(*a*) Sheets	Micafolium	Micafolium
	Mica cambric	Mica cambric
	Mica empire	Mica empire
	Machine-built commutator micanite	Machine commutator micanite
	Flexible micanite	Flexible micanite
	Segment micanite	Segment micanite
	Moulding micanite	Moulding micanite
(*b*) Tubes	All-mica tube	All-mica tube
	Protected mica tube	Protected mica tube
	Micafolium tube	Micafolium tube
(*c*) Tapes	Mica-silk tape (0·005 in.)	Mica-silk tape (single layer)
	Mica-silk tape (0·006 in.)	Mica-silk tape (2 layers)
	Mica-silk tape (0·008 in.)	Mica-silk tape (3 layers)
	Mica-paper tape	Mica-paper tape
(II) *Asbestos*		
(*a*) Boards	Bakelized asbestos boards	Bakelite asbestos
	Asbestos millboard	Asbestos millboard
	Semi-compressed asbestos, slate, or semi-compressed Uacolite, or Everite or Asbestone	Ordinary asbestos cement board
	Compressed "C" Uacolite	Compressed asbestos cement board
	Natural Syndanyo, or transite asbestos wood	Arc-resisting asbestos board
	Ebony Syndanyo, or ebony asbestos wood	Impregnated asbestos board
(*b*) Tubes	Asbestos tube	Asbestos tube
(*c*) Tapes	Asbestos paper tape (cut from asbestos paper)	Asbestos paper tape
	Asbestos woven tape	Asbestos woven tape
(*d*) Sheets	Asbestos paper	Asbestos paper
	Asbestos cloth	Asbestos cloth
(*e*) Cords	Asbestos cord	Asbestos cord
(*f*) Packings	Asbestos wool	Asbestos wool

TABLE C.

B.E.S.A. Class C Materials.

Fireproof and refractory materials such as pure mica, porcelain, quartz, etc.

	Usual trade name	Recommended standard name
(I) *Refractories*		
(*a*) Mica	Block mica	Block mica
	Amber mica splittings	Amber mica split
	Tower mica splittings	Tower mica split
	Moulding mica splittings	Moulding mica split
	Micafolium mica splittings	Micafolium mica split
	Flexible cell mica splittings	Flexible cell mica split
	Admiralty mica splittings	Admiralty mica split
(*b*) Porcelain	High-grade porcelain	High-grade porcelain
	Dry-process porcelain	Dry-process porcelain
(*c*) Natural mineral insulators	Slate	Slate
	Marble	Marble
	Lava	Lava

APPENDIX 4.

Classification of Commonly used Insulating Varnishes.

	Drying hours		Specific gravity at 15·5° C.	Redwood viscosity at 15·5° C.	Electric strength, in V/mil
	Oven	Air			
Oil Varnishes :					
Linseed oil, China wood oil blended with resins, gums and driers and thinned with hydrocarbon solvents (Petroleum naphtha, benzene, turpentine substitute, etc.)					
1. Baking coil varnish	6		0·855–0·875	30–50	700–900
2. Baking cloth varnish	8		0·830–0·875	30–50	700–900
Asphaltum varnishes :					
Native asphalts dissolved in benzine and frequently blended with linseed and wood oils, thinned with hydrocarbon solvents.					
1. Black plastic varnish	15		0·830–0·860	45–55	900–1 200
2. Black baking japan	6		0·870	—	600
Spirit varnishes :					
Lacs, gums and synthetic resins dissolved in denatured alcohol, acetone, etc.					
1. Black finishing varnish	5–10 min.	½	0·870–0·930	40–70	600
2. Clear finishing varnish		3	0·945–0·955	20–30	500
3. Mica sticking varnish		2	0·850–0·870	—	—
4. Shellac as a binder		2	0·975	60–70	900
5. Hard copal, for finishing, etc.		12	0·800–0·900	5–10	500
6. Synthetic for finishing	2–6	10–30 min.	0·980–1 000	60–80	200
7. Synthetic for paper treating	2–6	10–30	0·980	60–65	350
Pigmented varnishes :					
Oil varnishes loaded with lithopone or other pigments to improve their thermal and filling characteristics.					
1. Grey enamel	2–3	8–10	1·2–1·4	60–160	450

APPENDIX 5.

Physical Properties of Insulating Oils required to fulfil B.S.S. No. 148.

Grade	Sludge (Michie)	Loss by evaporation	Flash-point (Pensky-Martens)	Viscosity (Redwood), at 15·5° C.	Viscosity (Redwood), at 20° C.	Viscosity (Redwood), at 60° C.	Cold test	Disruptive strength	Acid value	Saponification value	Sulphur	General
	per cent	per cent						kV				
A (light) ..	0·1	2·0	170° C. ± 5° C.	$\not>$ 175	$\not>$ 145	$\not>$ 45	− 5° C. ± 5° C.	22	$\not>$ 2 mg KOH	$\not>$ 4 mg KOH	nil	The oil of each class shall be a pure hydrocarbon (mineral) oil, clean and sufficiently free from moisture or other matter likely to injure its insulating properties and shall satisfy the requirements set forth.
A (medium)	0·1	2·0	170° C. ± 5° C.	175–250	145–195	45–50	− 5° C. ± 5° C.	22	$\not>$ 2 mg KOH	$\not>$ 4 mg KOH	nil	
B (light) ..	0·8	3·0	155° C. ± 5° C.	$\not>$ 175	$\not>$ 145	$\not>$ 45	− 5° C. ± 5° C.	22	$\not>$ 2 mg KOH	$\not>$ 4 mg KOH	nil	
B (medium)	0·8	3·0	155° C. ± 5° C.	175–250	145–195	45–50	− 5° C. ± 5° C.	22	$\not>$ 2 mg KOH	$\not>$ 4 mg KOH	nil	
C	—	3·0	155° C. ± 5° C.	$\not>$ 300	$\not>$ 250	—	− 20° C. ± 5° C.	22	$\not>$ 2 mg KOH	$\not>$ 4 mg KOH	nil	

It is under consideration to modify the above clauses in certain respects with the possibility of admitting a wider range of oils having, for instance, slightly lower flash-points and higher loss by evaporation, but the tendency is to increase the value of the disruptive strength.

APPENDIX 6.

General Characteristics of Some Bituminous Materials.

Genus	Species	Member	Colour in mass	Fracture	Lustre	Specific gravity at 25° C.	Dropping point: Kramer-Sarnow	Dropping point: Ring and ball	Electric strength, V/mil
							° C.	° C.	
Bitumens	Petroleums	Non-asphaltic							
		Mixed-base							
		Asphaltic							
	Native mineral waxes	Ozokerite	White to yellow to brown	Conchoidal	Dull to waxy	0·85–1·0	60–93		100–140
		Montan wax		Conchoidal		0·90–1·0	77–93		
							88–93		
	Native asphalts	Pure or fairly pure	Black	Conchoidal	Bright	1·006–1·01	81·11		100–400
		Associated with mineral matter		Conchoidal	Dull	1·40–1·42	86·67		
	Asphaltites	Gilsonite	Black	Conchoidal	Bright	1·05–1·1	121–177	132–190	100
		Glance-pitch	Black	Conc. to rough	Bright	1·10–1·15			
		Grahamite	Black	Conc. to rough	Very bright to dull	1·15–1·2	177–315	187–329	
Pyrobitumens	Asphaltic pyro-bitumens	Elaterite	Black			0·9–1·05			
		Wurtzilite	Black	Conchoidal	Bright	1·05–1·07	Decomposes		
		Albertite	Black	Conc. to rough	Bright	1·07–1·10	Decomposes		
		Impsonite	Black	Rough	Semi-dull	1·10–1·25	Infusible		
		Asphaltic pyrobituminous shales	Brown to nearly black	Sub-conchoidal	Dull	0·9–1·32	Infusible		

APPENDIX 6.—*continued.*

GENERAL CHARACTERISTICS OF SOME BITUMINOUS MATERIALS.

Genus	Species	Member	Colour in mass	Fracture	Lustre	Specific gravity at 25° C.	Dropping point		Electric strength, V/mil
							Kramer-Sarnow	Ring and ball	
							° C.	° C.	
PYROBITUMENS —*continued*	Non-asphaltic pyrobitumens	Peat							
		Lignite							
		Bituminous coal							
		Anthracite coal							
		Lignitic and coal shales							
PYROGENOUS DISTILLATES	Pyrogenous waxes	Wax tailings	Yellow		Waxy	1·0–1·1	15·5–37		
		Petroleum paraffin	Pure white to yellowish	Conchoidal to rough	Dull to waxy	0·85–0·95	37–65	40–71	
		Peat paraffin							
		Lignite paraffin							
		Shale paraffin							
	Tars	Oil-gas tar	Black			0·95–1·1	−17 to −6		
		Water-gas tar	Black			1·05–1·15	−17 to −12		
		Pine tar	Brownish			1·05–1·1	10		
		Hardwood tar	Black			1·1–1·2	− 6		
		Peat tar	Black			0·9–1·05	4·4–15·5		
		Lignite tar	Yellowish brown to black			0·85–1·05	15–32		
		Shale tar	Brownish black			0·85–0·95	15–32		
		Gasworks coal tar	Black			1·1–1·3	− 3·9		
		Coke-oven coal tar	Black			1·1–1·3	− 3·9		
		Blast-furnace coal tar	Black			1·1–1·3	− 3·9		
		Producer-gas coal tar	Black			1·1–1·3	− 3·9		
		Bone tar							
PYROGENOUS RESIDUES	Pyrogenous asphalts	Residual oils	Black			0·85–1·05	−17·8 to 26	−12 to 35	120–350
		Blown petroleum asphalts	Black	Soft, hard, conchoidal	Bright to dull	0·9–1·07	26–148	37–162	
	Pitches	Residual asphalts	Black	Hard, conc.	Variable	1·0–1·17	26–107	37–121	
		Sludge asphalts	Black	Conchoidal	Bright	1·05–1·2	26–107	37–121	
		Wurtzilite asphalts	Black	Conchoidal	Bright	1·04–1·07	65–148	76–152	
		Oil-gas-tar pitch	Black	Conchoidal	Bright	1·15–1·3	26–135	37–148	100–300
		Water-gas-tar pitch	Black	Conchoidal	Bright	1·1–1·2	26–135	37–148	
		Wood-tar pitch	Black to brownish black	Conchoidal	Bright to dull	1·1–1·3	37–93	37–148	
		Peat-tar pitch	Black						
		Lignite-tar pitch	Black	Conchoidal	Very bright when fresh	1·05–1·2	32–121		
		Shale-tar pitch							
		Gasworks coal-tar pitch	Black	Conchoidal	Variable	1·15–1·4	26–148		
		Coke-oven coal-tar pitch	Black	Conchoidal	Variable	1·2–1·35	26–148		
		Blast-furnace coal-tar pitch	Black	Conchoidal	Variable	1·2–1·3	26–148		
		Producer gas coal-tar pitch	Black	Conchoidal	Variable	1·2–1·35	26–148		
		Bone tar pitch							
		Rosin pitch	Black	Conchoidal	Dull	1·08–1·15	48–93		
		Fatty-acid pitch	Dark brown to black	None to conchoidal	Bright	0·9–1·1	1·7–107	10–118	

APPENDIX 7.

Specimen Specification.

METROPOLITAN-VICKERS ELECTRICAL CO., LTD.
TRAFFORD PARK. MANCHESTER.

Process Specification No. 22365.

Varnish Treatment of Coils in Instrument Transformer Department.

General.—This specification details the process to be followed in the drying and dipping of coils in instrument transformer department.

Material.—Baking coil (0·875) varnish. P.S.* 1065
Motor spirit No. 3. P.S.* 1168-A

Varnish.—The varnish shall be thinned down with No. 3 motor spirit to a specific gravity between 0·870 and 0·875. This gravity shall be checked every day by means of a hydrometer and no coils shall be dipped if the specific gravity of the varnish is not correct.

Drying out of coils before dipping.—All coils for dipping shall be dried out for 8 hours in an oven at a temperature between 100–120° C. Care shall be taken when loading the oven that no coils are placed in contact with the steam pipe as this will damage the insulation.

Dipping and draining of coils.—The coils shall be removed from the oven and immediately dipped in the baking coil (0·870–0·875) varnish.

They shall remain below the surface until all bubbling has ceased or for a period of 5 minutes, should bubbles cease to rise to the surface of the varnish before this time has elapsed.

The coils shall then be removed from the varnish and hung up on the rack provided where they shall remain until all surplus varnish has drained off.

Second drying.—After draining the coils shall be replaced in the oven and dried at a temperature between 100–120° C. for 15 hours.

Subsequent dipping, draining and drying.—In cases where more than one dip is called for, the coils shall be redipped, drained and dried as detailed above. The second and subsequent dip shall take place immediately after the drying period which follows the previous dip.

Works Manager, (*Signed*) G. E. Bailey.
Chief Electrical Engineer, (*Signed*) J. S. Peck.

(*Signed*) A. P. M. Fleming,
Manager, Research and
Education Departments.

Date approved, 19.12.24.

* P.S. = Purchasing Specification.

APPENDIX 8.

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* The British Electrical and Allied Industries Research Association.

DISCUSSION BEFORE THE INSTITUTION, 23 APRIL, 1925.

Mr. E. B. Wedmore: Very great progress has been made in the last few years in insulation practice. Since manufacturers and users have co-operated through the Electrical Research Association in standardizing and improving their nomenclature and methods of testing, the precision with which insulating materials are selected for particular purposes has been greatly improved, as has also the quality of the materials. The development and use of improved and more precise methods of testing, simple and empirical as they may often appear to be, inevitably result in additions to our knowledge, and ultimately in improvements of products. The methods and results given in this paper are almost wholly of the type so much favoured by engineers, bordering on the empirical rather than on the methods of pure science. The engineer is daily faced with problems which will not submit at once to the methods of pure science, but which can be dealt with effectively for the immediate purpose by the empirical engineering method. I want, however, to insist upon the very great importance of fundamental research and the use of methods more searching and illuminating than those indicated in so many cases in the paper. The fuse test is a case in point. It is admirably adapted to give the engineer just the information he wants about materials used for a certain purpose, just as a foot rule is used

to pass men into the Guards. The foot rule was effective for the particular purpose but left us with a C3 population to be discovered during the European war. The fuse test and others like it will not prevent our having C3 insulating materials. Scientific methods, however, take time to develop and can best be discovered by people co-operating together and combining their facilities. Even with an establishment of the magnitude of Messrs. Metropolitan-Vickers Co. the expense is too great; but when large firms and small firms join together then we are able to tackle, on fundamental scientific lines, problems which the individual manufacturer finds beyond his means. Ultimately that is the only way in which rapid progress and far-reaching improvements will be made in the development of insulating materials. That there is room for improvement by such methods there can be no question. Some persons doubt the value of pure scientific work in a problem of this kind. It is true that one must always have the engineer to apply the results and even to advise the directions in which the research is carried on the industrial side; but anyone who has had close contact with problems of insulation will realize that there is a very great lack of knowledge as to the nature of the phenomena with which we are constantly faced. In the atmosphere of the works, stress is placed on continuous production of sound products. Bad samples and unexpected results are set aside as being something of no value immediately the stream of production can be made to flow smoothly. In engineering concerns the engineers do not realize how much new evidence passes under their eyes and is unnoticed because they are not wanting it immediately. In the calmer atmosphere of the Electrical Research Association we are able to turn these things over in our minds. There is no question that there is a great lack of fundamental data with regard to the nature of insulation and of conductivity in solids. If one takes such a simple case as conductivity in metals, when one looks into it one finds that there are conflicting theories as to the nature of conductivity there, and no one has yet been able to devise crucial tests to determine which of those theories is mostly right. Conductivity in non-metallic elements—pure elements—is a much more complicated phenomenon. What then may we expect in a commercial insulating material? Seldom do we even know what is in it. I am sure, however, that these difficulties will give way before methods of scientific attack. For our encouragement we have the clear analogy of the case of metallic alloys, the state of the art in which has been revolutionized by the scientific elucidation of the underlying physical phenomena. On page 439 the authors refer to fundamental research which it is hoped the Electrical Research Association will carry out on this subject, and they refer also to work which is in contemplation or in progress elsewhere. This Institution is the representative body of the industry, and whether we are going to do fundamental research in this country on a less extensive or on a more extensive scale than has been done elsewhere is for the members to say, and I hope they will show their sense of responsibility in the matter. This country has never lacked brains capable of dealing with pure scientific problems in an effective way. After all has been said, however, manufacturers in this country, including Messrs. Metropolitan-Vickers themselves, have no reason to be ashamed of the products which they turn out from day to day.

Mr. J. Rosen: I agree with Mr. Wedmore in regard to certain of the phraseology used in the paper, especially in regard to the statement that comparatively little scientific study has been given in this country to the production of high-grade insulating papers and pressboards. With regard to the tests proposed by the authors to be carried out on insulation, I would suggest that they should also consider the difficulties which arise due to repeated expansion and contraction, or to differences in expansion and contraction between the copper and the insulation. I find that in some cases after many years mica insulation apparently shrinks, but whether it actually does so or whether it powders I am not quite certain. This point is worthy of investigation. In regard to the specification for mica splittings —which I think is the generally accepted term—I agree with the authors that there is considerable difficulty in obtaining standard splittings. To give an example of the remarkable difference in the types of splittings, on one occasion we obtained an excellent splitting at a price of 1s. a pound. We had previously paid 2s. 6d. a pound. It was found that the splittings at 1s. a pound were far superior to those at the higher price. That is rather unusual, and I think that if steps were taken to get in touch with the suppliers more uniform material might be obtained.

Mr. A. R. Dunton: In Table 1 attention is drawn to the superiority of cotton-base papers for high-temperature work. These results could have been equally emphasized by mechanical tests. Further on we are told that the values of electric strength given on page 440 for pressboards are for tests carried out in air; but if the insulation had been thoroughly dried and impregnated in transformer oil, the values could with ease have been increased by approximately 100 per cent; and these would more closely correspond to the possibilities of this material for modern transformer practice. The authors also call attention to the use of paper-insulated conductors. This is rather a new development, and here again most remarkable results can be achieved by the use of properly selected papers. On page 442 the opinion is expressed that the adverse criticism against bakelite has been due to the large number of inferior grades of this material on the market. I would rather attribute this to the misuse of good material in many instances. Practically all bakelite boards and tubes may roughly be divided into three classes. I do not think many engineers actually realize this, because bakelite materials of the wrong class are often found in quite unsuitable places. We have numerous cases of bakelite materials which are really most absorbent and which are admirably suited for oil-immersed work, but of course will not do for open-air work of any nature whatever, unless they are adequately varnished. In another class of bakelite the paper has been so thoroughly impregnated with bakelite as to be impervious to humid conditions; and this is the class for use in air. Many people think that all bakelite is non-hydroscopic. This is incorrect. Certain classes

of bakelite are really excellent, and if engineers would use them properly they would get the results they desire. The E.R.A. fuse-wire test shows the deterioration of the various products resulting from this test; but it should be borne in mind that the test is extremely severe, and, although bakelite fails after the first test in actual practice, if suitable varnish protection is employed the material is quite capable of withstanding repeated flash-over tests without "tracking." Reference is made in the paper to the use of shellac-paper products for extremely high-voltage terminals. Whilst agreeing that this is possible where absorbent paper is used, equally good, if not better results can be obtained by the use of specially selected synthetic varnishes combined with non-porous papers of the greaseproof variety. In this case the paper used constitutes the main factor in withstanding the electrical stresses involved. The use of a non-absorbent paper calls, however, for very special scrutiny of the materials used, the important feature of which is to select the material at a stage in its treatment when all surplus vapour has been expelled, and yet sufficient adhesion has been retained, finally to produce a solid article. When this is done it is possible to eliminate the pressure baking mentioned on page **449**. At one time it was assumed that bakelite products could not be made without air pressure, but it is possible to do so if the materials are in the proper condition. For that reason I agree that the authors' statement on the subject is quite correct, but I would point out that the elimination of the pressure baking can only be carried out satisfactorily if the surplus gases have not been trapped in the material during the process of winding.

Mr. A. Collins: The manufacture of varnish-paper materials is now well established in this country but, as the authors have pointed out, in many quarters bakelite products have earned for themselves severe criticism. For a number of reasons this is not surprising. In the first instance there is the large number of proprietary grades on the market, both British and foreign. It is inevitable that there should be various qualities. There is also the question of the synthetic resin used in the manufacture of the material. Again, there are a number of proprietary grades on the market. The manufacture of this resin is a specialized chemical process, which has necessitated close co-operation between the manufacturing chemist and the insulation engineer. There are many qualities of synthetic resin, some of which are satisfactory, many indifferent, and some useless. The next point is the process of manufacture of varnish-paper products. It has been the practice of some manufacturers of electrical machinery to manufacture a certain amount of their own varnish-paper materials. They generally buy their raw material in a semi-finished condition, such as, for example, paper already treated with one or other of the many resins on the market. Whilst there are notable exceptions, in general it is unreasonable to expect the user of insulating materials to produce results comparable with the product of the specialized firm. There is a fourth point which has already been touched upon by Mr. Dunton. Those firms who may be regarded as the successful manufacturers of varnish-paper material find it necessary to manufacture several different grades, because the properties of the material have to be deliberately varied to meet different applications. This point is not fully appreciated, and it is by no means unusual to find engineers employing the wrong grade. I entirely agree with the authors' statement that the processes involved in the production of varnish-paper products are amongst the most highly technical with which the insulation engineer is called upon to contend. The work certainly calls for closer technical supervision than the manufacture of other insulating materials. I do not, however, agree with the authors when they state that there is probably no insulating material which causes producers "so much anxiety." I feel that the authors had no intention of creating in the minds of users the impression that such a remark may possibly convey. I am confident that, in the case of a specialized firm which has realized that proper scientific control and technical supervision are necessary for such a process, and has organized itself on proper lines with a view to the production of the material in large quantities, the atmosphere which prevails is not one of undue anxiety. It is a general belief that the extent of "tracking" is dependent upon the class of bakelite employed, and it would be useful if the authors would explain whether the tests illustrated on page **444** are typical of the results obtained on a large range of bakelite boards, or whether the behaviour of one grade only is shown. Whilst it may be difficult to eliminate the causes of tracking in special cases such as controller work—particularly oil-immersed controllers—this phenomenon is not such a serious matter so long as bakelite paper materials are correctly applied. In the class of varnish-paper insulators used in transformers and switchgear for which bakelite resin is considered a suitable material (and this excludes, according to the best practice in this country and the United States, very high-voltage terminals, for which natural resin is used) the design and conditions of test should be such that there is no possibility of tracking. The effect of a flash-over is entirely a question of the amount of power available. With sufficient power it is possible to damage any insulating material. I think that the authors are creating an unnecessary atmosphere of alarm when they suggest that a flash-over on the surface during a pressure test may create a conducting path. With the average testing equipment used in commercial work for testing switchgear and transformer insulators of the type and voltage manufactured in bakelite paper, there is little risk of such an occurrence when the flash-over occurs in air. I have seen many bakelite-paper insulators flashed over for demonstration purposes on an ordinary commercial testing plant without being damaged. The conditions under oil, of course, are more severe. One British firm of specialists can supply a varnish-paper board with a special surface which behaves very well under the fuse-wire test, and yet retains the mechanical properties of the bakelite-paper board. Commutator micanite—that is to say, the micanite used as separators between commutator bars—is a material in which many improvements have been made during the past few years. An impression still prevails in some quarters that a tolerance on the thickness of

plus or minus 1 mil, i.e. a difference of 2 mils between the maximum and minimum thickness, can easily be obtained. Present-day practice admits, however, that first-class commutator micanite may have a total variation between the maximum and minimum measurements of not more than 3½ to 4 mils at any point when measured with a micrometer having a head ⅜ inch in diameter. Closer figures can be obtained, but only at an increased cost which is not only commercially undesirable but unnecessary when suitable arrangements are made during commutator construction. What may be described as the average tolerance on the set of separators used for a commutator is a matter of considerable importance, because inaccuracies in individual separators accumulate to an extent which may be embarrassing in view of the number of separators required to make a commutator. Provided the commutator separators are purchased ready cut to size, modern methods of gauging and checking enable the specialized firm to keep the total tolerances on the whole set of separators within very fine limits. This feature constitutes a great advantage to the commutator builder. On page 448 the authors enumerate three leading methods of insulating stator conductors. Whilst the hand application of mica-silk tape leads to a higher mica content than the "Haefely wrap," the former method must, of necessity, be more expensive. It would be interesting to learn, therefore, whether in the authors' opinion the increased cost is likely to prejudice the more extended application of the mica-tape method, in spite of the technical advantages of the increased mica content.

Mr. H. C. Silver: One of our great difficulties in testing dielectrics is the complicated nature of the material. The electric strength of paper depends on several factors besides thickness and temperature, for instance the process of manufacture and the moisture content. Testing in oil introduces another factor, viz. porosity, and it is probable that the order of merit of the papers shown in Table 1 would have been altered had the tests been carried out in air. The authors hope that the Electrical Research Association will issue reliable data on the behaviour of insulating materials. That is a very difficult task, in view of the enormous variations one finds in testing insulating materials. The Electrical Research Association adopts the policy of preparing proposals for specifications which are based on the results of a large number of tests, and then the limits are set so as to eliminate the inferior materials. Those of us in close touch with the work of that Association realize fairly clearly the lines on which improvements can be made and, speaking entirely for myself, I am convinced that a stage has been reached in which the problem is not so much a technical as a psychological one. For instance, it is generally understood that bleaching affects the mechanical strength of paper. I was told recently, however, by a paper-maker that one is more likely to obtain superior paper made from a bleached pulp than a corresponding paper made from unbleached pulp, for the reason that the paper-maker takes more care in the manufacture of bleached paper than he does in the manufacture of unbleached paper. Another difficulty is the question of price. Electrical insulating paper should be regarded as a material altogether apart from ordinary paper, and if a user wishes to secure a really good insulating paper he must be prepared to pay an increased price for it. He can obtain improved papers if he is willing to pay for them.

Mr. W. P. Digby: The authors refer to the proposed standardization of the nomenclature of insulating materials. I was aware that the British Engineering Standards Association had been giving some attention to that matter. I think that the sooner a standardized list is issued the better it will be for the industry. Whether it will follow the lines of the authors' Appendix 3, I should be inclined to doubt. Some of the terms suggest the use of trade names, with which the B.E.S.A. does not wish to identify itself; and it would probably be better in one particular case to have used such an expression as "a woven fibrous material of the cotton type" than to have employed the name by which that particular varnished fabric is known in the shops. The question of the standardization of nomenclature is rather an old one. In a paper read before the Institution of Civil Engineers in 1910-11 the author of that paper, after urging the standardization of nomenclature, suggested that the standard of minimum insulation resistance of the machine on test should not take into account merely the pressure and the output of the machine, as is done to-day, but should also take into account the question of speed, because if the stator of the large, low-speed machine is compared with the stator of the 3 000-r.p.m. turbo-alternator, and if the clause given in the latest B.E.S.A. specification is applied, the insulation on the low-speed machine would have to be very much better than that on the high-speed machine, simply because the specification does not take into account slot areas. On page 440 the authors deprecate the standard high-pressure test when the machine is warm at the end of its test run, but those who test machines, as I frequently have to do, are in a rather difficult position. We can make an insulation-resistance test, and if we find the resistance low we can say, "Very well, take the pressure test another day." Ordinarily the time when we want to take a pressure test is when the machine is at the maker's works, not necessarily to find any fault with the drying out, which can easily be cured or which would even cure itself in practice, but in order to track down as quickly as we can any defects due to the carelessness of the winder, through any abrasion of the material or cutting through fibrous insulating materials. The only place in which we can take a pressure test is at the maker's works, and it will be very little satisfaction to a purchaser if he is expected to take a pressure test after delivery. It would be very much less satisfactory, I fancy, to the average manufacturer. One or two speakers have deprecated the references in the paper to the development work in this country, and I feel that probably the authors would wish to revise their references on page 446 to the porcelain manufacturers here. These manufacturers are working under conditions of considerable difficulty, but they are working under and delivering high-tension insulators complying with the British Standard Specification—a specification which is quite as severe as that of any other manufacturing country. They are fully

alive to the necessity of, and are fully desirous of, developing further. In some cases there is a deficiency of high-tension testing equipment; but in dealing with such questions as the chemistry of clays and the physics of the materials they use, my own impression is that the manufacturers are fully alive to the problems; and I think that the authors may wish to modify that particular remark. Generally, with regard to the insulation of electrical machinery, I should say that, up to the outbreak of war, there were two parallel developments in progress. In this country we were developing moulded mica insulation for extra-high-tension machinery, and were leading the Continent in the quality of our work. On the other hand, for low-tension machines, in regard to the use of compressed fibrous materials, my impression is that the Continent was ahead of us. In 1913 I visited a large German works and was shown with pride their latest insulation on a 6 000-volt alternator. They assured me it was the first machine on which they had used that method, but it was the standard moulded mica insulation which was being turned out in this country five or six years before that. So that I feel that even if we did lag behind in regard to the compressed fibrous materials, our woven and pressed fibrous materials were quite as good as any produced on the Continent, and our practice in regard to the use of moulded mica was far in advance of theirs. The authors speak of the necessity of co-operation between the user and the manufacturer. This is well recognized, but it has only been within the last few years, and with the increasing use of embedded temperature detectors, that intelligent co-operation has been possible. In the modern power station, with its thermocouple embedded in the windings, it is possible to keep a proper life history of the machine, and in due course, if trouble does arise, we can see whether or not the insulation is to blame. An examination of the insulation of some of the machines which were built 20 years ago, when insulation was rather a matter of rule-of-thumb, shows that the fibrous insulation has become quite brittle, and it is surprising that the machines have withstood working pressures of 200 or 500 volts for so long. Many of the younger of those present are likely to die of old age before the generators being built to-day in this country break down through failure of insulation, always provided that the loads are not in excess of the specified limits to which the machines have been built.

Mr. H. D. Symons: There has been steady and marked improvement in methods of insulating during the past few years, not always accompanied by an improvement in the materials used. Indeed the reverse is often true, and one experiences many instances where service has only been met by intelligent and careful use of material. The need for standardized methods of tests for insulating materials is becoming increasingly urgent, and the Electrical Research Association is doing sterling work in this direction. Referring to the insulation test on page 440, it is often of great service to study the materials which have been used in the construction of machines and apparatus, as an aid in determining what insulation tests should be applied. The authors' proposal that the nomenclature of insulating materials should be standardized has my hearty support, but I would urge the great desirability of the adoption, or at least the serious consideration, of the use of numbers. Numbers are just as easy to memorize as names, and moreover they have the distinct advantage that they allow of future developments. For the sake of example, the grading of insulating materials, such as papers, under insulating paper No. 1, insulating paper No. 2, and so on, instead of the authors' list of names given in Appendix 3, would allow for extension to any extent. This idea can be applied to each separate class of product. The subdivision can be varied and the number of materials of any given class can steadily be added to without confusion. It has also the advantage of eliminating the use of such expressions as "special quality" and other similar phrases which give no indication whatever of the material. Unless something like this is seriously attempted the list of materials in use in 25 years' time will commence to tax our vocabulary. The results given in Table 3 are very interesting, but I cannot quite share the authors' enthusiasm for the treatment of the cotton cloth with a weak solution of caustic soda, as the figure given shows very little improvement over that obtained with boiling water. The treatment with varnish of synthetic resin-paper tubes and boards to prevent tracking is very effective, provided the right varnish is selected and its application correct. Referring to page 445, I entirely agree with the authors that the percentage of mica in built-up insulation should be always definitely specified as a percentage by volume and not by weight. This percentage by weight is becoming very generally adopted, and it is entirely misleading as it gives no mental conception of the density of the material. Referring to page 448, I would draw the authors' attention to their omission to emphasize the necessity for pressing long armature and turbo-generator coils before insulating. Whether a solid or flexible type of insulation is to be applied, not only is this pressing necessary but some treatment should be applied to produce very close adhesion between turns; it is impossible to attempt to insulate a large coil if this is not done. The authors, dealing with the question of varnish treatment on page 449, boldly state that they advocate a hot dipping method of treatment instead of vacuum impregnation. I entirely agree with them that this method is certainly efficacious and in a great majority of cases superior to the vacuum method of treatment, and is much more economical in practice. It will no doubt sound to many a retrograde step, and yet there is absolutely no need whatever to attempt to vacuum-impregnate anything with varnish if the varnish has been properly designed for impregnating purposes and is kept in proper condition. The authors advocate baking temperatures of 100-120° C. I not only entirely support this, but consider that temperatures even exceeding this figure can be used with advantage. There is nothing to fear—in many cases nothing but benefit will accrue—from baking at these temperatures, provided a good class of varnish has been used. Indeed, temperatures of 200° C. can be used with benefit in the hands of skilled operatives; this is the whole crux of the matter and is dealt with on the last page of the paper, where the authors emphasize the necessity of having skilled operatives for

insulation work. It must be admitted that skilled operatives have not been trained in the past and it is only now becoming recognized how important this aspect of the question is. With skilled operatives, intelligent selection and use of materials, there is no question that the insulating materials of to-day have a life comparable with the rest of the machine, provided the same proper supervision be given to the insulation as to the rest of the machine.

Mr. W. J. John: At the top of page 446 the authors refer to porcelain. This reference contains statements which are misleading, and I trust that the authors will adopt the suggestion made by a previous speaker and considerably modify it. British porcelain manufacturers are said to be lagging behind American and Continental manufacturers in the attention they are giving to research. Also they are said to be conservative. In the course of my work I have been brought into intimate contact with one of the largest firms of porcelain manufacturers in this country, and this particular firm has a staff of chemists and engineers who are engaged in investigating the various problems associated with the production of high-grade porcelain. Moreover, the research work is not hampered by lack of the necessary testing apparatus, in spite of the fact that the high-voltage testing equipment for this class of work is very expensive. This particular firm has spent during the last 2 or 3 years over £20 000 in providing high-voltage and high-frequency testing apparatus. The above facts, I think, refute the suggestion that all British porcelain manufacturers are not paying sufficient attention to research in their particular industry. Secondly, they are charged with being conservative, but I have found absolutely no signs of conservatism in my dealings with them. On more than one occasion, in fact, they have made radical alterations in long-established methods just to suit what must to them have appeared to be a whim on the part of the designer of the insulator. One thing which particularly impressed me was the way in which they tackled a new and difficult problem concerning the machining of fired high-tension porcelain. They tackled it with great enthusiasm and made a great success of it. In my considered opinion the charges of neglect of research and of conservatism made against the porcelain manufacturers of this country are unfounded. The authors express a fear that the British porcelain manufacturer will be excluded from the high-grade electrical porcelain market of the future, but my own opinion is that he will hold a very high place there.

Mr. P. Dunsheath: In Table 1 are given the ageing characteristics of two fibres extensively used in cable manufacture, and rather striking results are obtained. Five fibres are mentioned, viz. cotton, sulphate wood pulp, hydrated chemical wood, manilla and jutes, and they are placed in the order of merit as they appear on the test after heating. I shall confine my remarks to chemical wood and manilla. After 40° C. these two remain in the same order—the chemical wood superior in every case. This confirms some tests which I made a few months ago on the dielectric power factor and mechanical properties of these materials. Some engineers still consider that manilla is the only insulating paper that can be used on a cable, but in the cable industry itself there is no unanimity on this subject. Only quite recently I saw some curves which seemed to prove that manilla was better than wood pulp, quite as conclusively as the authors' figures prove the opposite —figures which my results support. In view of this conflicting evidence it occurs to me that there may be some other factor which has been overlooked: are we in these figures comparing fibres or are we comparing something else? I am wondering whether the order in Table 1 indicates the ease with which the fibres become impregnated rather than the electrical characteristics of the fibres themselves. The authors do not say what method of impregnation they used, and it would be interesting to have their views on that aspect. On page 440 they deal with lignification and suggest that the more highly lignified fibres deteriorate more rapidly. This hardly seems to confirm the comparison made in Table 1 as I do not think that manilla can claim to be more highly lignified than wood pulp. In Table 3 the insulation resistance of cotton is only given for samples after they have been subjected to air of 70 per cent humidity, but it is very unusual, I think, for cotton to be used under those conditions. In order to show the merits of the system and to show whether the dielectric resistance is improved by treatment, either by caustic soda or by ordinary bleaching, the samples should be dried before the test is taken, or possibly varnished if that is more convenient. It is interesting to note that the improvement in the electric strength is not nearly so great as that in the insulation resistance; the latter jumps from 34 to 1 000, but the electric strength varies from 95 to 94 on washing in water and up to 109 with the 0·5 per cent solution. It would be of great assistance if the authors were to state what kind of variations were obtained between the breakdown strengths of the different samples under identical conditions. My experience with breakdown tests is that with exactly similar conditions one would get very much greater variations than are used here to claim an advantage for the method. It is to be regretted that the authors dismiss the theory of dielectrics so summarily. It is obvious to anyone who has worked on the subject of dielectrics that any investigator who has collected the amount of information contained in the paper has certainly at the same time formed some views on the theory which might perhaps benefit other workers.

Mr. H. S. Holbrook (*communicated*): As a transformer engineer, I was particularly interested in the specimen specification for the varnish treatment of coils given in Appendix 7. It is about 20 years since the British Thomson-Houston Co., Ltd., found such specifications desirable. This specification is very similar but we find it worth while to measure the temperature when taking the specific gravity and to give the operators a table showing how the specific gravity should vary with the temperature. To keep the temperature of the treating rooms practically constant, summer and winter and all day, would involve an impracticable expense for ventilating and heating plant. During the war, considerable difficulties were experienced with supplies of spirit thinners, and we came to the conclusion that measurements on varnish baths of viscosity instead of

density would help matters, but before we had finished the development of a suitable viscosimeter for workshop use the spirit situation improved. The authors give some viscosity figures in **Appendix 4**; have they ever considered making routine measurements of viscosity? The specimen treatment specification uses the term "second drying" where we find it preferable to refer to "baking" of the varnish. As a matter of fact our more modern equipments use two separate ovens for the "drying" before the coils are dipped, and for the "baking" of the varnish after dipping. The drying ovens are complete with vacuum pumps and moisture condensers, and whilst we specify a minimum drying time, with alternative periods of free air and vacuum, we also specify that the drying is to be continued until no more moisture is given off by the charge of coils, and as shown by the condenser gauges. Some years ago the development of automatic recording hygrometers for transformer drying ovens was considered, but this was stopped by the war and since then we have not had time to return to the problems. The Western Electric Co., U.S.A., have developed an instrument for average humidities (see *Bell System Technical Journal*, April, 1924). Our transformer baking ovens are equipped with large fans for forced ventilation, the removal of varnish fumes and the supply of fresh oxygen, and we heartily agree with the authors regarding the futility of "stewing" coils in varnish fumes. One important point in connection with pressboards is the linear shrinkage which may occur during their manufacture. Another is the "coil shrinkage" which may occur when the coils are continuously immersed in hot transformer oil and exposed to fluctuating mechanical forces due to short-circuits, overloads, etc. Some pressboards have excellent machining properties; others mould well but none seem very satisfactory in riveted constructions. The industry needs an insulating cement which can be applied cold, sets quickly and is proof against hot oil. Perhaps the best test for indicating the propensity of an oil to sludge in service is the Synder life test given in A.S.T.M. documents, but it takes weeks, sometimes months. Mr. Nuttall's surface-tension test has the great advantage of being quickly carried out, but it remains to be seen if it will give consistent results when applied by different physicists in different laboratories, and whether it will always grade oils in the same order as the Michie test does. An important feature of bituminous materials used for "filling" apparatus—not mentioned by the authors—is the "free flowing point" or minimum temperature at which they can be poured. Unless comparatively expensive electrically heated and stirred melting pots are used, there is a great risk of these materials being overheated to an extent sufficient to ruin their disruptive-strength properties. Another class of bituminous material on which research is required is the "solid" fillers for fine-wire coils of oil-immersed apparatus. We agree with the authors that insulating processes, to be successful, need machines especially designed for the purpose, and that it does not pay to try to use up scrapped machine tools. Particularly is this the case in the manufacture of varnished-paper products, which, as the authors rightly state, call for the closest possible scientific control and technical supervision. It is a matter for regret that we in this country are so far behind the Swiss and Americans in the manufacture of these materials. This is one of the cases where the facility of thermostatic control with electric heating makes that method profitable. We cannot too strongly support the authors in their statement that the complete prevention of dirt is essential, even to the provision of double doors, linoleum-covered floors, and dust-screens over windows, etc. This was very forcibly brought to our notice during the winding of some aeroplane coils with 2-mil wire by hand on semi-automatic machines. The operators had a perfect record for freedom from breakdowns while the dust-screens were in position, the floor oiled, etc., but, if these precautions were relaxed, trouble at once occurred on test. A material not mentioned by the authors on which there has been some discussion as to whether it should be included in classes B or C of the International Electrotechnical Commission, is cured concrete. We find it a very successful material for fireproof current-limiting reactors.

Mr. H. Warren (*communicated*): The authors refer to the work of Moureu and Dufraisse, and I am able to confirm that the work of these two investigators may possibly have a useful effect in the arresting of certain changes that take place in insulating materials. Hydroquinone has, I believe, already been used as an anti-oxygene in the case of transformer oil, and the possibility of minimizing tracking in synthetic materials by the same agency has been investigated in the laboratories of the British Thomson-Houston Co. This property of tracking, possessed to such a pronounced degree by phenol-formaldehyde resins, together with their inflexibility, calls for the exercise of great caution and discretion in applying these resins to the general run of electrical insulation. Promising work has been done by Albert in the development of flexible phenol-formaldehyde resins, but up to the present no great application has been made of these. I can substantiate what the authors say in regard to the difficulties of manufacturing uniform synthetic bonded-paper tubes, and the difficulties in the control of the manufacture of the resins themselves are responsible for considerable variations in the varnishes used by the electrical manufacturer for this purpose. Phenol-formaldehyde resin, as a bonding medium, has received a great deal of support on account of its mechanical dependability at high temperatures, and in such cases as transformer work this is unquestionably an important consideration. It is, however, quite possible to make shellac-bonded cylinders, etc., for transformers, which have mechanical and electrical properties at least equivalent to those of synthetic bonded structures at the highest temperatures met with in service, and, bearing in mind the drawbacks of the synthetic resin, it is often preferable to retain shellac. I have had no successful experience of blending synthetic resin with shellac varnish, but several useful composite insulations, such as those for turbo-alternator slip-ring leads and controller shafts, have been prepared, using separate superimposed layers of shellac-bonded micanite or paper, and synthetic bonded paper or cotton fabric. Where mechanical robustness and resistance to abrasion are essentials, an outer coating

of synthetic bonded fabric or fibre is used, but where there is danger of surface leakage the outer layers are shellac-bonded. Both arrangements are given a finishing coat of oil baking varnish. The authors mention the applications of synthetic bonded asbestos, and there is no question that synthetic bonded asbestos fibre and fabric for packing blocks and distance pieces is of use where mechanical reliability at high temperatures is to be ensured. The common but erroneous idea that these particular asbestos compounds are non-inflammable must, however, be deprecated. The insulation of slip-ring sleeves can be very satisfactorily carried out with carefully selected asbestos paper bonded with suitable synthetic varnish, this compound being particularly immune from mechanical damage in the shops and flaking in operation at high speeds. These disadvantages are commonly encountered in the use of micanite. Synthetic bonded cotton fabric made from the right resin produces very satisfactory contactor spools and slot wedges, and this compound is generally useful where mechanical rigidity is essential. The most successful application of synthetic resin has undoubtedly been in the production of moulded insulations, and there is no question that the synthetic moulding is of unique service to the electrical engineer. Wherever the design can be so arranged that the danger of "tracking" is eliminated, the moulding of intricate shapes to a high degree of accuracy and finish, and the inertness of the material to reagents and high temperatures, are features of which considerable advantage can often be taken. The development of phthallic anhydride-glycerine synthetic resins, which do not track and have superior adhesive qualities, is being followed up, and the more recently devised urea-formaldehyde resins might possibly be utilized in the electrical industry.

Percentage of mica in wrappings.—The authors' comments in connection with the percentage of mica in mica wrappings are very interesting, and whilst I agree that 35 to 40 per cent of mica by volume undoubtedly yields good results, I would express the opinion that it is a distinct commercial possibility to obtain figures of the order of 50 per cent. The expression of the percentage by volume is certainly preferable to the rather misleading practice of stating the percentage by weight. There are, however, very considerable experimental difficulties in determining the percentage by volume directly, and a good, quick method of carrying out this test is greatly needed. As bearing on the authors' comments upon this point, I would mention that a certain mica tape recently investigated contained 70 per cent of mica by weight, and only 32 per cent by volume.

E.R.A. fuse-wire test.—We have made an investigation of the value of the E.R.A. standard fuse-wire test for arc resistance and tracking, as described in their publication A/S9 and referred to in the paper, and are of the opinion that this test forms a very useful indication of the properties under consideration.

Asbestos products.—The practical efficacy of asbestos tape in coil insulation is rather doubtful, not only because of the difficulty noted by the authors in securing thin tape, but because of the absorbent nature of the material. The predominant advantage of asbestos is its resistance to the action of flames, but any really efficacious water-resisting treatment of which I have knowledge seriously impairs this property. The whole question of rendering windings fireproof is one in which there is room for considerable advancement. Asbestos is, of course, of considerable use as a filler in moulded insulations, where resistance to high temperatures, and the additional mechanical strength arising from the length of fibre, are required.

Rubber latex.—The authors mention that the improvement of papers and pressboard by the agency of rubber latex does not (owing to the ageing propensities of this substance at 80° C.) present any features of great interest to the electrical engineer. There is, however, possibly a future for latex as a bond in moulded compositions.

Varnish treatment.—Under the heading of "Varnish Treatment" the authors refer to the falling into disuse of vacuum impregnation, but I should not have thought that the substitution of hot dipping had become so generally complete.

Wood.—The authors do not appear to make any reference to wood in the paper, and I would mention that although synthetic bonded paper and fabric rods and tubes have, to some extent, displaced wood for such purposes as tension rods and cross-arms in switchgear, there has been some advance in the treatment of wood for such purposes during the past few years. Properly selected and treated wood is still widely used for a variety of purposes, and it is often difficult to provide an equally practicable substitute.

Fibre.—In Appendix 1 fibre tubes and cylinders are specified for mechanical use only, but it may be well to bear in mind that the fuse-wire test reflects very favourably upon fibre, which actually in practice makes a satisfactory fuse tube or carrier.

Recommended standard names.—In connection with Appendix 3, in which certain useful suggestions are made as to standard names, it would appear preferable to avoid the use of such specialized semi-proprietary names as Empire silk, "Gilling's" twine, Bakelite kraft paper, Lacwatt No. 49, and Formite (bakelite) varnishes.

Messrs. K. G. Maxwell and **A. Monkhouse** (*in reply*). Mr. Wedmore criticizes the paper on account of the fact that the tests which we included in it were very empirical tests; that is to say, works tests. All of us on the manufacturing side are looking forward to the assistance that we hope to get from the Electrical Research Association, in order to make those tests more scientific and, at the same time, no more difficult to carry out in the works laboratory. If short tests and quick tests can be made which are at the same time scientific and which give us the figures we want, naturally we should prefer to use such tests rather than empirical tests; and that is one of the things we are looking forward to in the future.

Mr. Dunsheath has referred to the absence of anything more than a short paragraph dealing with the theory of dielectrics. We very much wish that we had had space and more time to discuss that subject, because it is extraordinarily interesting, but in our opinion it is a subject for at least a whole evening's discussion and probably then finality would not be reached. What

we hope to see is a comprehensive paper dealing with the subject in itself. This paper is more on the practical side, involving the application of materials and processes.

Mr. Digby has referred to the tracking down of defects in machinery, and made a plea in favour of high-pressure tests instead of the method which has been suggested here; but in our opinion the defects due to faulty windings or careless workmanship should be, and could be, found out, possibly by introducing the high-pressure test with the machine in a cold condition, even before it was put on to its first temperature run. After the first preliminary run all large machines are generally recognized to be in their most dangerous state, and a high-voltage test under these conditions should be regarded as exceptionally severe.

With regard to the question of standardization of terminology, Mr. Digby and other speakers have commented upon the unsuitability, from the standard point of view, of some of the names suggested in Appendix 3. We quite agree with that. As pointed out in the paper itself, these names are only intended to be suggestions. The Appendix is exactly as it was drawn up three or four years ago for use in the factory, where names which had been in use for 20 years were already in existence and where very much confusion was being caused by the use of other names. In choosing the names, therefore, we are afraid that the question of British standardization was not taken into consideration.

In dealing with the question of standardization, Mr. Symons also suggests that it might be more suitable to classify the materials and to grade them under numbers. His remarks particularly refer to papers. This is a subject which all those who have had anything to do with the preparation of specifications for works or for individual needs have very seriously considered and we are afraid that on the whole we do not agree with Mr. Symons's proposal. What is really very much more suitable, in our opinion, consists of standardized names, which must be carefully chosen to avoid anything in the nature of trade names, examples of which are recorded under Mr. Warren's remarks. As far as papers are concerned, we think that we are right in saying that the Electrical Research Association have already given standardized names to the majority of papers used in modern insulation practice.

In regard to the tests showing the electric strength of different papers, Mr. Silver and Mr. Dunsheath have both referred to the figures in Table 1. These tests were made in oil advisedly, because such papers are almost invariably used in a treated condition, not in either hot or cold air, but in some other medium. For this reason a standard transformer oil was chosen, because it was the medium about which we knew a certain amount. With regard to the time of immersion in oil before a test is made, when we began this investigation it was quite obvious to us that this time element would have an effect upon the result, as Mr. Dunsheath suggests, so that all the samples were soaked for a period of 24 hours before the tests at the temperatures indicated. With regard to the point of lignification, raised by Mr. Dunsheath, his opinion is that the sulphate wood pulp would be more highly lignified than manilla, but that is open to argument and is largely a question of the purity of the wood-pulp paper.

Coming to Table 2, referring to pressboards, Mr. Dunton in his remarks criticized us for not making the tests in oil. We agree, and if these tests had been made in oil we should have got very much higher electrical test-figures. Concerning the application of paper, we think Mr. Dunton's remark that paper-insulated conductors represent a new use would be best emphasized by noting its adoption as far as the heavy machine industry is concerned. Paper insulation of cables has been a standard thing for many years.

Mr. Rosen deplores the lack of research on high-grade insulating papers and pressboards, but in our opinion his remarks should be confined to the past, as there is at present a considerable amount of activity in this direction and really good work is being enthusiastically done by some of the leading manufacturers of this class of material; the presence of Table 2 should confirm this. We would endorse Mr. Silver's remarks concerning the care which should be exercised in the manufacture of paper and the stress which he lays on the fact that electrical papers should be regarded as a material altogether apart from ordinary paper.

In a communication from Mr. Holbrook reference is made to the linear shrinkage of pressboard, but this can be overcome by suitable curing before use.

Mr. Symons refers to the figures given in Table 3, and suggests that boiling water would have given results equally as good as caustic soda. That is very largely true, but the point we would emphasize is that although the cloths mentioned by Mr. Symons are treated and scoured before they are made up into varnish cloth, this is not true of cotton used as the insulation on wires. In the case of ordinary double-cotton wire the cotton is absolutely untreated from the time it leaves the cotton plant until it goes on the wire; and we were more concerned with this cotton insulation when making the investigation. It is particularly important in the case of cotton used on telephone flexible cords and similar wires where it is not impregnated and where a very high insulation resistance is essential.

Mr. Dunton, in his remarks with regard to varnished-paper products of a bakelite class, points out that various classes of bakelite are available and are generally recognized. That is one of the things which the Electrical Research Association have done for us. They have clearly defined three grades of bakelite products—varnished paper and varnished fabric products—and also two grades of varnished-paper and varnished-fabric products made with natural gums and resins. With regard to the production of varnished-paper products using a highly non-porous paper of the grease-proof variety, as suggested by Mr. Dunton, that of course requires special precautions, and the success of this is dependent to some extent upon the purities of the gums used.

Mr. Collins and other speakers refer to the question of tracking. He asks what particular kind of bakelite was used in making the test mentioned at the top of the illustration showing specimens after the fuse-wire test. During the course of these tests, we tested nearly

every bakelite on the market, and with one exception they all broke down on either the first or second exposure, whereas vulcanized fibre and some of the more despised insulating materials stood up to 20 tests. With regard to the pressure test being a cause of tracking, the ordinary pressure test, made with about 10 kW, to which Mr. Collins refers, will, of course, not have any effect. A flash can be produced across the surface and there will be no ill-effects, but for power work we think that pressure tests using a greater amount of power are desirable. When one applies something like 400–500 kV with 500 kW behind it, serious damage is likely to result if anything goes wrong.

Mr. Collins also suggests that insulating materials of the bakelite class should not be used in positions where they are exposed to power arcs or heavy discharges. We cannot always cater for that. If we take, for instance, the case of a high-tension bushing on a 110 000-volt transformer which is connected more or less directly to the overhead lines, and as with such high voltages it is often common practice not to employ lightning arresters, it will be agreed that we are liable to get a discharge across the terminal. This may possibly be caused by surges due to lightning.

As pointed out by Mr. Symons, the tracking effect can be minimized by suitable protective varnishes, or, as mentioned in a communication from Mr. Warren, by the use of superimposed layers of shellac-bonded material on a synthetic bonded interior. Experimental work to eliminate tracking is also being done, but the use of hydroquinone and other methods have not up to the present made sufficient advance to warrant adoption.

In a communication from Mr. Holbrook, it is suggested that British-manufactured synthetic materials are not up to the standard of those manufactured in Switzerland or America. Fortunately, we have been engaged on the testing of a large number of synthetic boards and tubes and can definitely state that material is being manufactured in this country giving test-results actually superior to those obtained on materials from the sources mentioned.

Both Mr. Rosen and Mr. Collins have touched on the subject of mica. We sympathize with them concerning the variation that exists in mica splittings and we hope that a definite grading of this material will soon be finally achieved. Mr. Rosen also refers to the expansion and contraction of the conductor in mica-insulated machines. He is there touching on what is a very real trouble, particularly in the high-speed machine with long cores. We think that modern methods of manufacture and the control of processes are largely getting over that trouble. We appreciate Mr. Symons's remark concerning the necessity for steam pressing of turbo bars—this of course is always done and very materially helps in raising the percentage by volume of the mica content, which has been mentioned by several of the speakers.

On the subject of porcelain, Mr. John and other speakers have referred to the remark in the paper taxing British porcelain manufacturers with not being so energetically engaged on research work as some of those in other countries. We are afraid that in the past there has been a tendency for British manufacturers to neglect research, and it is therefore very encouraging to note that active steps are now being taken to remedy this. All of those present at this meeting will realize what British brains and British scientists have done for the whole industry, and that we have led and still lead in insulating materials. The paper was not intended to belittle what has been done and what is being done, but rather to urge that the effort must be kept up. Much research needs to be done if we are going to keep the place we have hitherto held.

Several speakers have mentioned the omission of various subjects, such as the treatment of wood for insulation purposes, the use of asbestos, etc., but each of these subjects would provide matter for full discussion in detail and the paper has had to be confined to a more general consideration of the improvements effected in insulation practice of recent years.

North-Eastern Centre, at Newcastle, 14 December, 1925.

Mr. J. Rosen: In my opinion the authors do not give British producers of insulating material the credit they deserve; a good deal of research has been carried out here during past years, and is still being carried out, though perhaps it has not been so much advertised as elsewhere. Engineers responsible for the operation of electrical machinery are naturally the most severe critics and undoubtedly they have done a great deal from their experience to help the manufacturer; after all, the best place for research is in plant under operating conditions. Although much of the matter published may be considered to be only of academic interest, it undoubtedly forms a basis for practical investigation and, by increasing our understanding of the problems, will lead to practical improvements which will enable the known insulation to be used for even higher voltages than at present. Naturally, it is the one weak spot in the insulation that limits the stress to which the remainder of the plant is subject. If we could be assured of the complete uniformity in our insulating materials, we should be able to turn out more efficient plant at lower cost. There are three papers * which might with advantage be added to the authors' already fairly complete list; they give a simple conception of the mechanism of breakdown. The authors refer to the practical conditions of testing before putting electrical plant on load for the first time. For the largest machines it is to be recommended that the windings should be dried either on short-circuit or otherwise before pressure-testing. By this means the volatile matter or moisture is driven off and the windings are better able to withstand the test. These precautions are essential where plants are wound on site. Wherever possible, alternator stators should be

* Report of Committee on Electrical Insulation Division of Engineering, National Research Council: "The Problem of Insulation," *Journal of the American Institute of Electrical Engineers*, 1923, vol. 42, p. 618. J. B. Whitehead: "Gaseous Ionization in Built-up Insulation," *ibid.*, 1924, vol. 43, p. 19; also discussion, *ibid.*, 1924, vol. 43, p. 1165. J. L. R. Hayden and C. P. Steinmetz: "High-Voltage Insulation," *ibid.*, 1924, vol. 43, p. 36.

wound completely in the works to enable the windings to be thoroughly dried. It is worth a little thought and expense to overcome transportation difficulties to attain this result. On the question of mica products, mica has the inherent disadvantage of its poor mechanical properties, and steps have always to be taken to ensure that under all conditions of temperature the mica insulation is so prepared that it will not flake. In most designs it is very necessary to provide some form of mechanical support. I agree that there should be a limit in the amount of class A allowed in class B material, and should be interested to hear if the percentage of mica of 35–40 which is recommended for class B insulation is the percentage in the micafolium only, and does not take into account the possibility of using other material on the outside of the insulating tube for protection. If the authors do not include the latter, the figure appears to be low; I should expect it to exceed 50 per cent in a reasonable design. The authors refer to the use of casein as a binding base for a group of moulded materials. Have they had experience in the use of such material? I understand that it is inflammable, but I have not been able to find out under what conditions it failed. Another subject for investigation, which no doubt has been carried out by individual firms, is the comparative advantage of hard moulding insulation, and an insulation containing oil which enables the insulation to retain its properties of flexibility. There are advantages perhaps to be claimed for both. I have found that where long conductor bars have to be insulated for high voltages it is advisable to have some form of flexible varnish between the insulating tube and the conductor, or to use a flexible insulation to enable it to allow for the unequal expansion of copper, iron and the insulation at different temperatures. Otherwise there is the danger of the insulation cracking under load conditions.

Mr. F. H. Williams: One of the most interesting post-war developments of the big electrical and other manufacturing concerns of this country is that of the research department, which has now become an integral part of the manufacturing machine, with the result, for example, that many manufacturing processes are now controlled or supervised by technical men specially trained for the job. A day spent in a research department such as that with which the authors are connected is most interesting. Although the paper contains a considerable amount of valuable data, particularly from the point of view of the manufacturers, I am rather disappointed that the paper does not contain more information regarding recent improvements in insulation for extra-high-tension work. The only reference to this subject appears to be on page 444, where rough figures are given for the diameter and overall length of a condenser bushing for 220 kV. I am also disappointed that the authors have not given some information regarding recent improvements in testing methods. This is a natural corollary to improvements in insulating material and, whilst it could well form the subject of a paper itself, I think that the value of the paper would have been enhanced if the authors had given a résumé of the more recent improvements in testing methods. I had hoped to hear something about dielectric-loss measurements as applied to condenser bushings and also something about high-frequency tests. It is most important in connection with insulation for super-tension work that we should be able to determine by tests not only whether the material is likely to break down in service but also what is the actual factor of safety. For e.h.t. condenser bushings such as those referred to by the authors, the usual over-potential test is, I consider, practically useless as a test to determine whether the bushing will be satisfactory in service. In my opinion the only satisfactory method of testing such bushings is that involving an actual dielectric-loss measurement, and I believe that this will become a standard test for such apparatus in the near future. With regard to the testing of insulating oils referred to on page 447, I should like to ask the authors whether the test referred to has been approved by the B.E.S.A. Sub-Committee on Insulating Oils. There have been many attempts to find a substitute for the Michie sludge test, and some of these appeared at first sight to be very attractive but were subsequently found to give misleading results. Such a test was one which aimed at reducing the lengths of the test by substituting oxygen for air. This, it has been found, is not a test for sludge but for acid-forming properties. It is therefore of primary importance that any test put forward as a substitute for the present sludge test should be examined exhaustively before being adopted as a substitute for the present standard sludge test. I should also like to ask whether the vertical oil test-gap has been approved by the B.E.S.A. Sub-Committee. I looked into this matter some time ago and was informed that the vertical gap does not always give the same results as the horizontal gap. With regard to fibre, it would be very helpful if the authors could say how one could always ensure that a satisfactory variety was used, as many of the fibres at present on the market have practically no insulating properties and are liable to lead to trouble due to shrinkage.

Mr. T. Carter: The authors have covered the ground so thoroughly that little is possible by way of discussion except comment on details. What they say in Section 3 of the paper about the danger of the flash test is most valuable as a reminder of a too-often forgotten risk run in the application of the test, and I should like to emphasize the importance of keeping it in mind. Enamel insulation, mentioned in Section 4 (*a*), Sub-Section (3), under the heading of "Coverings for Wires," has been, in my experience, of doubtful value for anything but windings of purely cylindrical form. Anything approaching a sharp corner in a former is more or less fatal, and leads too often to breakage of the enamel. The effectiveness of the insulation is probably greatly increased by adding a single cotton covering to the enamel covering. Towards the end of Sub-Section (5) of Section 4 (*a*), leatheroid is mentioned as an excellent material for slot linings. It should be made quite clear that this is not a recommendation of leatheroid for slot insulation, and that it is referred to merely as providing a lining with a smooth and slippery surface, so that, when used in addition to the real slot insulation, it prevents damage when the coil is slid into the slot. Leatheroid alone has been used for the slot insulation of very small

machines, where the room is very limited, but except in such special circumstances it would obviously be bad practice to depend on it as the sole insulator. Coil-winding machines are mentioned in Section 5 [(*a*) and (*b*)], under the heading of "Coil Insulation"; they are admirable for their purpose, no doubt, but it may be pointed out that their full advantage is secured only when a large amount of repetition work can be done on them, and that if, on the other hand, an attempt is made to use them for single coils or only a few coils of one winding, the time spent in rearranging the setting of the machines when the winding is changed may seriously diminish their economy. Later in Section 5 [(*a*) and (*b*)], under the heading of "Assembling, Taping, etc.," reference is made to micanite for use between commutator segments. It appears to be growing more and more difficult to get even built-up micanite, at a reasonable price, that will wear evenly with the copper, and undercutting of the micanite, with its attendant disadvantages, is more and more frequently resorted to. As a mechanical process, it seems quite wrong to run an inflexible carbon brush, however good the spring behind it, on a cylindrical surface full of gaps; but presumably the exhaustion of supplies of the material that would make it unnecessary may have to be regarded as an indication that the second-best practice must be adopted. The value of the process specifications referred to in Section 5 (*c*) cannot be overestimated. Even with them something is left on which to exercise skill and judgment in supervision; but without them too much hangs on the presence of some particular person whose going away would so interrupt things that an entirely fresh start might have to be made. They are like family recipes, or even heirlooms, passing from one generation to another, and not to have them would be to head straight for failure in essential processes, and would result in constant lack of certainty in manufacture. Finally, I commend to users of electrical plant the plea in Section 5 (*d*) for their close co-operation with the manufacturers, to the end that both of them may profit from the experience of each. The user sees the plant in practical operation, and he looks at it thus from an angle entirely different from that of the designer or manufacturer. He may see things that could obviously be improved, and it is a real kindness on his partto point them out, so that under the scrutiny of all who are interested, and with the collective thought of many different persons applied to it, that which is bad may disappear, and that which is good may become still better than it was.

Mr. J. W. Jackson: Although the paper is of very great value from the point of view of the choice of materials for insulating apparatus, I am unable to agree with the remarks made under the heading "Standardization of Methods of Testing Insulation." The method usually obtaining is that of drying out and testing for insulation values at definite intervals. After the megger indicates infinity for a length of time the contractor is usually prepared to agree to a power voltage test to be applied while the machine is still hot. The particular value of this method of testing is that the apparatus is tested under conditions more nearly analogous to those that will obtain in service, as all apparatus is more or less hot in service. The method suggested by Mr. Hartshorn, viz. the bridge method of measuring leakage losses, is one that savours too much of the laboratory. What is the authors' opinion as to the value of bakelized insulation when subjected to service conditions where employed on the insulation of, say, switchgear which is occasionally called upon to function even with water in the oil? It is often a difficult matter to prevent water finding its way into the oil, and, so far as can be seen at present, the small amount of water with which oil will combine appears to be sufficient to cause the more or less complete deterioration of insulation where applied directly on conductors charged at over 3 000 volts. This has been observed on insulators made during the past 12 years. The disintegration allows the flat sheet and also cylindrical type of insulation to become separated into its component layers and in addition very much enlarged and at the same time softened, mechanically weak, and of a low electrical insulation value, allowing leakage to occur between layers. These remarks apply to insulation manufactured more than 4 years ago. It is at the same time realized that, provided frequent inspection is made and any doubtful pieces are immediately replaced, this type of insulation is still the most satisfactory from most points of view, in that it is very much more robust than porcelain, and, if it fails, does so at a comparatively low rate of speed, thus allowing sufficient time for replacements before serious risk is being run.

Messrs. K. G. Maxwell and **A. Monkhouse** (*in reply*): Mr. Rosen's statement that in our paper we have given insufficient credit to British producers of insulating materials, must be contrasted with his addition to our bibliography of three American works. We are, however, obliged to him for drawing our attention to these. Mr. Rosen and Mr. Jackson criticize our remarks upon the danger of the flash test immediately following the initial temperature run; Mr. Carter, however, agrees with us. Our point is that, even after sufficient drying-out to permit that initial temperature run, the immediate imposition of an overpotential test on complex insulation, from which certain volatile matter cannot have been completely freed but merely displaced from the hotter portions (only determined by actual running conditions) and therefore not yet "dried out" from the cooler end-windings, is an unnecessarily severe test condition. In giving the figure of 45 per cent mica by volume in wraps on, say, alternator bars, this includes the whole of the insulation on the bar as passed into the slot, and the volumetric measurement is taken on the finished bar ready for insertion. We agree with Mr. Rosen's experience of allowing for flexibility between copper and iron with the long slot-length of the modern machine. He refers to the inflammability of casein-bonded materials, but "Galolith" (mentioned in the paper) and "Erinoid" are two superior forms of such products which are practically non-inflammable. We have no experience of their extensive use yet, but as their true properties become recognized they will undoubtedly find a place amongst moulded parts.

Mr. Williams is right in suggesting that details of improved methods of testing would form the subject

of a separate paper, and we only make a plea for the standardization of the method of testing insulating materials at any stage in their production or use, as well as for standard nomenclature.

On the question of "factors of safety" for electrical tests, we do not consider that the various methods of making tests are to-day sufficiently defined to enable us to use such a term. The Nuttall test on insulating oils has not been approved by the B.E.S.A. Sub-Committee on Insulating Oils, probably because it has not been extensively developed, and we agree with Mr. Williams that it is of the utmost importance to establish clearly the relation between such a test and the life conditions of insulating oils in modern plant. The B.E.S.A. Sub-Committee have expressed the opinion that with good average quality of insulating oil it is immaterial whether the vertical or horizontal gap be used, and a suitable test gap of the vertical type has already appeared on the market. With regard to fibre and the necessary tests to ensure quality, B.E.S.A. Specification No. 216 has just been issued covering vulcanized fibre, but we readily agree with Mr. Williams that many of the fibres at present on the market have extremely indifferent properties viewed from the point of view of a stable product suitable for insulating purposes. As in the case of several other similar materials which have had trade uses quite apart from those of the electrical engineer, the only satisfactory method of ensuring reliable material is to develop a source the consistency of which has been established by a series of tests and observed ageing conditions, and to endeavour to keep the supplier tied to an established source and so to control the manufacture, transport and storage of the material that rejections from the consumer's point of view are kept down to reasonable figures. It can be said that makers are now appreciating this condition of supply, and considerable improvement has been effected through such channels. Freedom from shrinkage depends almost entirely upon this procedure and upon keeping the material, up to the actual time of treatment, to a known moisture content bearing an agreed relation to the natural absorption percentage (which may vary from 4 per cent to 20 per cent and even higher) for that particular density of material.

Mr. Carter is right in assuming that in referring to slot "linings" we mention leatheroid as a mechanical protection and not as an insulator. He speaks of the difficulty of getting uniform wear between segmental micanite on commutators and the copper, but modern practice confirms the use of undercut micanite segments on commutators and permits the employment of a harder micantite of lower bond content, giving easier assembly to permanent dimensions of the commutator and reducing the cost of "seasoning."

Mr. Jackson raises an interesting point in connection with the deterioration and ultimate failure at low voltage of bakelite products due to moisture absorption and disintegration. It is our opinion that this class of material, namely a synthetic resin varnish-paper product, has, since its development some 18 years ago, up to recent years certainly given trouble in the manner described by Mr. Jackson. Present-day high-grade bakelite products, however, where the raw materials have been closely watched and complete bakelization has taken place, may be considered to be unaffected by moisture under service conditions, although with severe exposure to moisture they are hygroscopic to between 3 and 4 per cent. Even under these latter conditions, however, the material will not separate along the laminæ and will retain its electrical properties with age. This requires the closest supervision and control in the whole of the manufacturing stages, both of the gum itself and of the composite material, and only the highest-grade products can be considered in this category. The mechanical advantages, however, of using such a material have not been unduly stressed by Mr. Jackson.

We are glad to hear that both Mr. Rosen and Mr. Carter advocate the linking up of the operating engineer's experience with that of the designer, and we should like to commend to the notice of the members the wide possibilities of using the Institution's discussions throughout the country as a channel whereby valuable exchange of experiences of electrical machinery can be debated with mutual advantage.

THE EFFECT PRODUCED ON THE PERMEANCE OF A LAMINATED POLE-CORE BY THE INSERTION OF A SOLID STEEL FIXING-PIECE.*

By B. HAGUE, M.Sc., Associate Member.

(*Paper first received* 18*th September, and in final form* 18*th November,* 1925.)

SUMMARY.

The object of the paper is to discuss the effect produced on the permeance of a laminated pole-core which has been perforated with an axial circular hole into which a solid steel fixing-piece or plug is inserted to receive the bolts which attach the core to the yoke. The theory of a core in which the plug fits perfectly in the hole is first examined, and curves for the permeance calculation are prepared. The theory is then extended to apply to a plug which fits loosely in the hole, the influence of imperfect fit being shown by a numerical example.

The application of the theory in practical cases is shown, in general, to be satisfactory. In the extreme example of pole-cores used in water-wheel generators, where numerous secondary matters have to be considered, the discrepancy between theory and practice is explained. The utility of the theory in calculating the permeance of transformer limbs consisting of laminæ clamped together by insulated bolts is shown, and uses in certain problems of current conduction, e.g. in a perforated busbar, are suggested.

(1) INTRODUCTION.

The object of this paper is to describe some solutions of certain problems in magnetic design which have a practical interest in connection with particular forms of construction used in dynamo-electric machinery and related apparatus.

It is the practice of some manufacturers to construct salient poles, especially for small dynamos, in the way shown in Fig. 1 (*a*). The pole-core and shoe is made up of a pile of stampings riveted or bolted together. The assembled pole is attached to the yoke by inserting through the laminæ a solid bar or pin of steel of square or circular cross-section and passing the fixing screws through the yoke into this steel piece, which is tapped to receive them. A better construction is thus obtained than would be the case if an attempt were made to drill and tap the pole to take the fixing screws directly. The problem presented by this construction is a troublesome one for the designer, since the insertion of the steel piece through the laminæ introduces considerable uncertainty into the calculation of the permeance of the path of the main flux through the pole-core. The complication of the problem is such that a rigorous mathematical solution is out of the question, but the author has frequently been asked by designers if it would not be possible to obtain even an approximate solution which would indicate the magnitude and general nature of the effect to be expected. It is the purpose of this paper to give such an approximation and to discuss its practical value.

Electrical design contains a number of problems of a similar character. For example, the laminated limbs of a transformer core are held together by insulated steel bolts as shown in a simple instance by Fig. 1 (*b*). It is of practical interest to inquire what will be the influence of the perforation of the laminæ and the partial filling of the hole by magnetic material upon the permeance of the limb, or of the section thereof associated with one bolt and comprised between the chain-dotted lines.

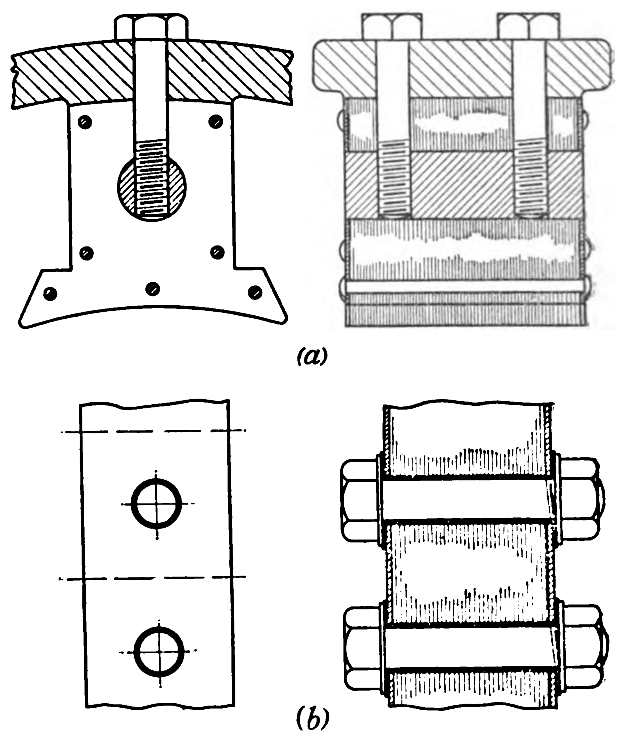

FIG. 1.—Diagram showing arrangement of steel fixing-piece in a pole-core, and of insulated bolts in a transformer limb.

In either of these problems an exact solution cannot be found, for two important mathematical reasons. The first is the extreme analytical difficulty of satisfying exactly the conditions imposed by the *geometry* of the magnetic masses. The second is the practical impossibility of dealing mathematically with the properties of

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ferromagnetic materials. It becomes necessary, therefore, to lay down three definite assumptions in order to bring the problem within the scope of mathematical analysis. These assumptions are as follow :—

(i) The perforated material is supposed to extend to infinity in all directions.

(ii) The pin or plug is assumed to have infinite axial length and is supposed to be situated centrally within the hole, which it may partially or completely fill.

Solutions restricted by these geometrical assumptions will closely apply to a pole-core which is of large peripheral width and radial length in comparison with the diameter of the steel pin, or to a transformer leg in which the width of the plates and the spacing of the bolts are large compared with the diameter of bolt. The flow of flux will, moreover, be two-dimensional, and will not be seriously different from that actually occurring. The precise effect of these assumptions in limiting the application of the solutions to practical instances will be discussed at a later stage.

The third and most serious assumption is of a physical nature and is as follows :—

(iii) The permeable materials of which both perforated mass and plug are composed are assumed each to have constant permeability and to be magnetically isotropic.

Actual magnetic materials are ferromagnetics, in which the relation of magnetizing force to magnetic induction is extremely complex, following the law of the magnetic hysteresis loop; this relation is not expressible in mathematical notation. The assumption means that the materials are supposed to be paramagnetics in which, throughout the region of each material, the permeability is constant and independent from point to point of the magnetic induction, i.e. the magnetization characteristics of the materials are linear. Such magnetic isotropy is approximately found in ferromagnetic materials when worked at very high or very low inductions, since the permeability is then not much influenced by the actual value of the induction. The solutions found under the paramagnetic assumption, however, fortunately enable limits to be assigned between which all practical ferromagnetic cases must lie.

In the following Sections solutions are worked out for two cases, (*a*) where the plug fits tightly within the perforated mass, so that only two media are involved, and (*b*) where the plug is separated from the mass by an annular space of air or other magnetically indifferent medium, involving three media.

(2) Perforated Mass with Close-Fitting Plug.

In Fig. 2 take the origin at the centre of the circular cross-section of the plug and use polar co-ordinates r, θ in the plane of the paper. The cylindrical plug has a uniform permeability μ_1 and cuts the paper normally; it is of infinite axial length. Outside the plug, and magnetically contiguous with it on the cylindrical surface, is the medium of permeability μ_2 extending to infinity in all directions both in and perpendicular to the plane of the paper. This represents the material which has been perforated with a circular hole of radius a and infinite axial length, the hole being filled with material of permeability μ_1.

At a considerable distance from the origin a uniform magnetizing force H_0 is supposed to be impressed in the medium μ_2 from right to left. Thus at a very great distance from the plug there exists in the perforated mass a uniform field of induction density $B_0 = \mu_2 H_0$ directed parallel to XO.

In virtue of the presence of the magnetic field, the distribution of which in the neighbourhood of the plug is to be investigated, magnetic potentials Ω_1, Ω_2 must exist in the two media. These potentials must be such as will satisfy Laplace's equation of continuity in their respective regions, viz.

$$r\frac{\partial}{\partial r}\left(r\frac{\partial \Omega}{\partial r}\right) + \frac{\partial^2 \Omega}{\partial \theta^2} = 0 \quad . \quad . \quad . \quad . \quad (1)$$

where $\Omega = \Omega_1$ within the plug and $\Omega = \Omega_2$ outside it. Moreover, at the interface $r = a$ between the two

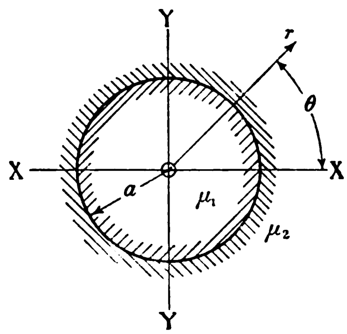

Fig. 2.—Co-ordinates for the field in a perforated mass with a close-fitting circular cylindrical plug.

media the potentials must ensure (*a*) equal tangential magnetic forces in the media,

$$-\left(\frac{1}{r}\cdot\frac{\partial \Omega_1}{\partial \theta}\right)_{r=a} = -\left(\frac{1}{r}\cdot\frac{\partial \Omega_2}{\partial \theta}\right)_{r=a} \quad . \quad . \quad (2)$$

and (*b*) equal radial magnetic inductions in the two materials,

$$-\mu_1\left(\frac{\partial \Omega_1}{\partial r}\right)_{r=a} = -\mu_2\left(\frac{\partial \Omega_2}{\partial r}\right)_{r=a} \quad . \quad . \quad (3)$$

Experience suggests that in a problem which has the central symmetry just postulated the solution must be sought in terms of two-dimensional cylindrical harmonics, the most general expression for a potential being

$$\Omega = \sum_1^\infty r^n(P_n \cos n\theta + Q_n \sin n\theta) + \sum_1^\infty r^{-n}(R_n \cos n\theta + S_n \sin n\theta)$$

where n takes integral values and the coefficients P_n, Q_n, R_n and S_n are independent of r and θ and are to be determined. It is clear from the physical conditions of the problem that the magnetic force in either medium

must be finite, i.e. $-\partial\Omega/\partial r$ and $-\partial\Omega/r\partial\theta$, the components of H, must remain finite, Ω being interpreted as Ω_1 inside and as Ω_2 outside the plug. Again, since the flux passes from right to left it is also clear that the axis YOY is a line of symmetry for the magnetic potential, the latter being zero thereon. To the right of YOY, whether above or below the axis of X, the potential is positive and increasing; to the left it is negative and increasing. It is obvious, therefore, that both Ω_1 and Ω_2 have symmetry in the four quadrants determined by a cosine law; hence sine terms are inadmissible and the general expression becomes

$$\Omega = \sum_1^\infty [P_n r^n + R_n r^{-n}] \cos n\theta$$

Inside the plug r has values lying between 0 and a; hence for the magnetic force to remain finite, terms involving r^{-n} must vanish, so that

$$\Omega_1 = \sum_1^\infty A_n r^n \cos n\theta \quad . \quad . \quad . \quad . \quad (4)$$

where A_n is written in place of P_n of the general form. Again, in the material outside the plug r lies between a and infinity; hence the magnetic force will only be finite if all the terms involving r^n vanish except that for which $n = 1$, hence

$$\Omega_2 = P_1 r \cos\theta + \sum_1^\infty \frac{R_n}{r^n} \cos n\theta \quad . \quad . \quad (5)$$

The coefficients A_n, P_1 and R_n can now be easily found from the boundary conditions.

The radial and tangential components of magnetic force at an infinite distance, where the field has the uniform value H_0 from right to left, are, from equation (5)

$$-H_0 \cos\theta = -\left(\frac{\partial\Omega_2}{\partial r}\right)_{r=\infty} = -P_1 \cos\theta,$$

$$H_0 \sin\theta = -\left(\frac{\partial\Omega_2}{r\partial\theta}\right)_{r=\infty} = P_1 \sin\theta;$$

whence $$P_1 = H_0$$

Substituting equations (4) and (5) in equations (2) and (3) gives

$$\sum_1^\infty n A_n a^{n-1} \sin n\theta = H_0 \sin\theta + \sum_1^\infty n \frac{R_n}{a^{n+1}} \sin n\theta$$

$$\mu_1 \sum_1^\infty n A_n a^{n-1} \cos n\theta = \mu_2 H_0 \cos\theta - \mu_2 \sum_1^\infty n \frac{R_n}{a^{n+1}} \cos n\theta$$

Comparing coefficients we get:—

$$\left.\begin{aligned} A_n a^{n-1} &= R_n/a^{n+1} \\ \mu_1 A_n a^{n-1} &= -\mu_2 (R_n/a^{n+1}) \end{aligned}\right\} \text{when } n > 1$$

$$\left.\begin{aligned} A_1 - (R_1/a^2) &= H_0 \\ \mu_1 A_1 + \mu_2 (R_1/a^2) &= \mu_2 H_0 \end{aligned}\right\} \text{when } n = 1$$

Solving these equations makes

$$A_n = R_n = 0; \quad A_1 = \frac{2\mu_2 H_0}{\mu_2 + \mu_1}; \quad R_1 = H_0 a^2 \left(\frac{\mu_2 - \mu_1}{\mu_2 + \mu_1}\right)$$

which, on substitution in equations (4) and (5), gives

$$\Omega_1 = \frac{2\mu_2}{\mu_2 + \mu_1} H_0 r \cos\theta \quad . \quad . \quad . \quad . \quad (6)$$

$$\Omega_2 = H_0 \left[r + \frac{a^2}{r} \left(\frac{\mu_2 - \mu_1}{\mu_2 + \mu_1}\right) \right] \cos\theta \quad . \quad . \quad (7)$$

Now the magnetic potential of a uniform field H_0 parallel to XO is clearly given by $H_0 r \cos\theta$; hence the field within the plug is also uniform and due to a potential $2\mu_2/(\mu_2 + \mu_1)$ times as great. The field inside the plug is therefore uniform, parallel to XO, and has a magnetic force $2\mu_2 H_0/(\mu_2 + \mu_1)$; the induction density in the plug is therefore $2\mu_1\mu_2 H_0/(\mu_2 + \mu_1)$, or $2\mu_1/(\mu_2 + \mu_1)$ times as great as the induction in the external mass at a great distance from the plug. In other words, the magnetic force in the plug is μ_2/μ times the value in the mass at a distance from the hole; whilst the induction therein is μ_1/μ times as great as the induction imposed on the mass at infinity, where μ is written for the average of the permeabilities of the plug and external mass.

Distribution of the field.—The magnetic equipotentials can be traced from equations (6) and (7) by writing $\Omega_1 =$ constant and $\Omega_2 =$ constant in the two media, successive equipotentials being characterized by equal increments in the appropriate potential. Greater interest applies to the lines of magnetic force (or to the lines of induction, which in paramagnetic materials are related to the former by a mere numerical factor) which cut the lines of constant magnetic potential at right angles. By the theory of orthogonal trajectories, the value of $d\theta/dr$ on an equipotential passing through any given point must be equal to the value of $-dr/(r^2 d\theta)$ on the line of force or induction intersecting the equipotential normally at the same point. Applying this within the plug, from equation (6) we get

$$\frac{d\theta}{dr} = \frac{1}{r} \cdot \frac{\cos\theta}{\sin\theta}$$

on the equipotential, so that on the orthogonal

$$-\frac{1}{r^2} \cdot \frac{dr}{d\theta} = \frac{1}{r} \cdot \frac{\cos\theta}{\sin\theta}$$

which on integration gives as the equation to the lines of induction in the plug,

$$r \sin\theta = \text{constant} \quad . \quad . \quad . \quad . \quad (8)$$

which is a uniform field parallel to XO.

Similarly, in the perforated mass from equation (7) we have

$$\frac{d\theta}{dr} = \frac{1 - (a^2/r^2)[(\mu_2 - \mu_1)/(\mu_2 + \mu_1)]}{r + (a^2/r)[(\mu_2 - \mu_1)/(\mu_2 + \mu_1)]} \cdot \frac{\cos\theta}{\sin\theta}$$

Putting this equal to $-dr/r^2 d\theta$ and integrating, gives as the equation to the lines of induction outside the plug

$$\left[r - \frac{a^2}{r} \left(\frac{\mu_2 - \mu_1}{\mu_2 + \mu_1}\right) \right] \sin\theta = \text{constant} \quad . \quad (9)$$

The lines of induction derived from equations (8)

and (9) have been plotted in Fig. 3 in some typical instances. Fig. 3 (*a*) shows the concentration of the field into the plug when the material thereof is twice as permeable as the surrounding perforated mass; Fig. 3 (*b*) shows the dispersal of the field from the plug when its material is only half as permeable as that of the mass. Fig. 3 (*c*) is the ultimate limiting case of a highly permeable mass perforated by a hole unfilled by permeable material. In all cases it is to be noted that the configuration of the field depends only on the ratio μ_1/μ_2 and not on the absolute values of μ_1 or μ_2; also that the least value of μ_1 or μ_2 is unity.

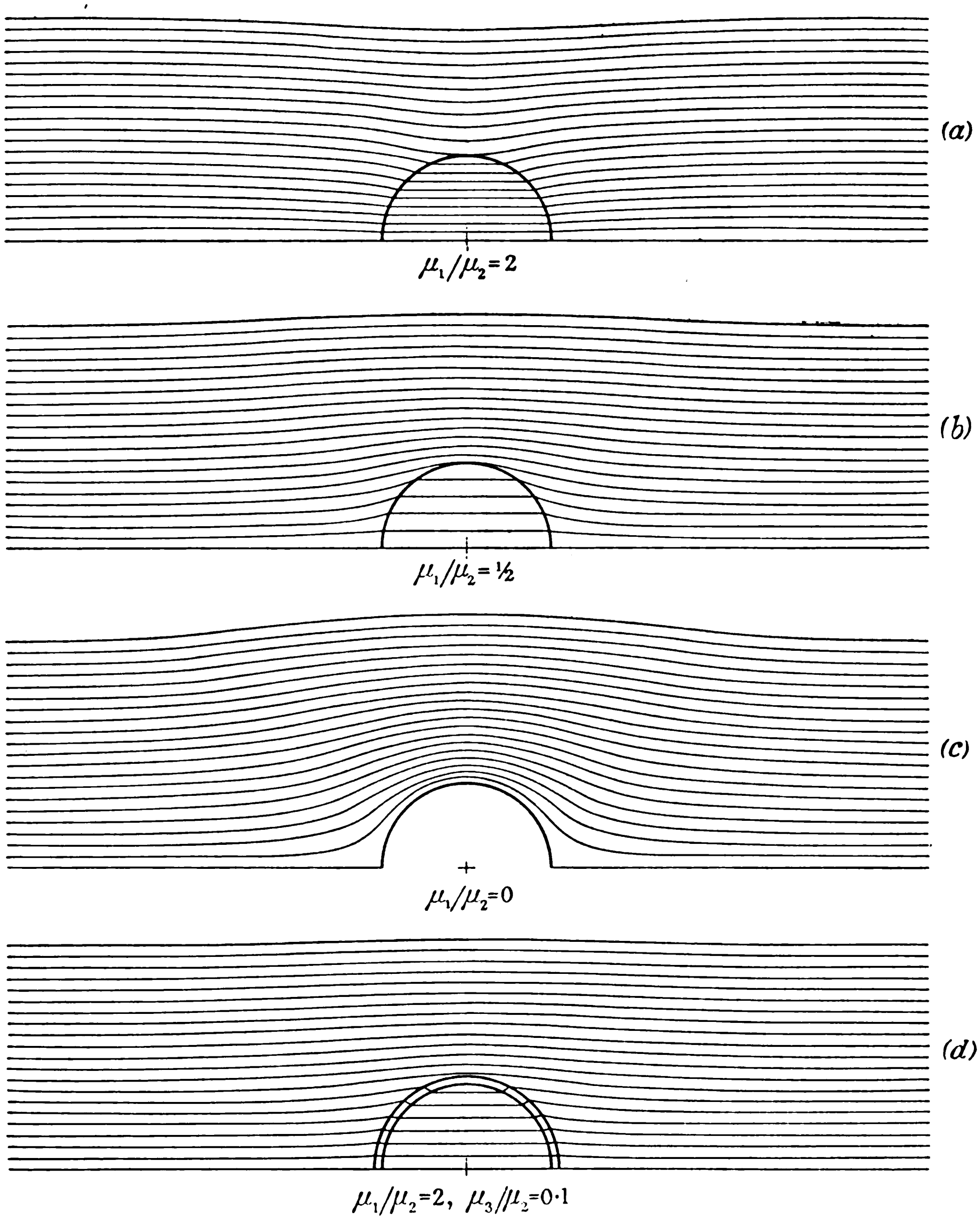

Fig. 3.—Diagrams showing the effect of a plug of circular cross-section on a uniform magnetic field in an iron mass.

Permeance of the field.—Consider a portion of the field bounded by lines of induction which pass through the points $(R, \pi/2)$, $(R, 3\pi/2)$ and by the equipotentials through the points $(l, 0)$, (l, π). Fig. 3 shows that these lines of induction and equipotentials are practically straight lines parallel to OX and OY respectively, provided that R and l each exceed about $3a$. They therefore bound a plate of closely rectangular shape $2R$ cm broad and $2l$ cm long of permeability μ_2; the plate is perforated with a hole of diameter $2a$ completely filled with material of permeability μ_1, as in Fig. 4. It is required to find the permeance of such a plate per cm of thickness parallel to the axis of the hole when a flux flows from right to left in response to the difference of magnetic potential impressed between the ends of the length of the plate.

For brevity write $k = \mu_1/\mu_2$ in equations (6) and (7), then

$$\Omega_1 = \frac{2H_0}{1+k} r \cos\theta$$

$$\Omega_2 = H_0\left[r + \frac{a^2}{r}\left(\frac{1-k}{1+k}\right)\right]\cos\theta$$

In the plug, the magnetic force across the Y axis is

$$-\left(\frac{\partial\Omega_1}{r\partial\theta}\right)_{\theta=\pi/2} = \frac{2H_0}{1+k}$$

showing that the field is uniform between $r = 0$ and $r = a$. The magnetic force across the Y axis in the perforated plate is

$$-\left(\frac{\partial\Omega_2}{r\partial\theta}\right)_{\theta=\pi/2} = H_0\left[1 + \frac{a^2}{r^2}\left(\frac{1-k}{1+k}\right)\right]$$

between $r = a$ and $r = R$.

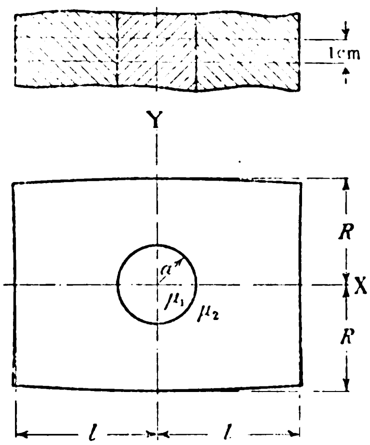

FIG. 4.—Diagram giving the dimensions of an approximately rectangular plate of iron with a permeable plug of circular cross-section.

The magnetic induction across the Y axis is, inside the plug,

$$B_1 = \frac{2H_0}{1+k}\mu_1 = 2H_0\mu_2\frac{k}{1+k}$$

and outside the plug

$$B_2 = H_0\mu_2\left[1 + \frac{a^2}{r^2}\left(\frac{1-k}{1+k}\right)\right]$$

The total flux of induction crossing the Y axis is

$$\Phi = 2\int_0^a B_1 dr + 2\int_a^R B_2 dr = 2H_0\mu_2\left[R - \frac{a^2}{R}\left(\frac{1-k}{1+k}\right)\right]$$

From equation (7) the difference of magnetic potential between l and $-l$ is

$$\Omega = 2H_0\left[l + \frac{a^2}{l}\left(\frac{1-k}{1+k}\right)\right]$$

Hence the permeance per cm axial length is

$$\mathbf{P} = \frac{\Phi}{\Omega} = \mu_2\frac{R - (a^2/R)[(1-k)/(1+k)]}{l + (a^2/l)[(1-k)/(1+k)]} = \mu_2\mathbf{P}' \quad (10)$$

The quantity $\mathbf{P}'$ may be termed the "geometric permeance" of the strip, since it depends merely on the relative dimensions of the plug and the perforated mass and on their relative permeabilities. Now let

$$\alpha = \frac{\text{Central width of plate}}{\text{Diameter of plug}} = \frac{2R}{2a} \quad . \quad . \quad (11a)$$

$$\beta = \frac{\text{Length of plate in direction of flux}}{\text{Diameter of plug}} = \frac{2l}{2a} \quad (11b)$$

$$\gamma = \frac{1-k}{1+k} = \frac{\mu_2 - \mu_1}{\mu_2 + \mu_1} \quad . \quad . \quad . \quad (11c)$$

Then

$$\mathbf{P}' = \frac{\alpha - (\gamma/\alpha)}{\beta + (\gamma/\beta)} \quad . \quad . \quad . \quad . \quad (12)$$

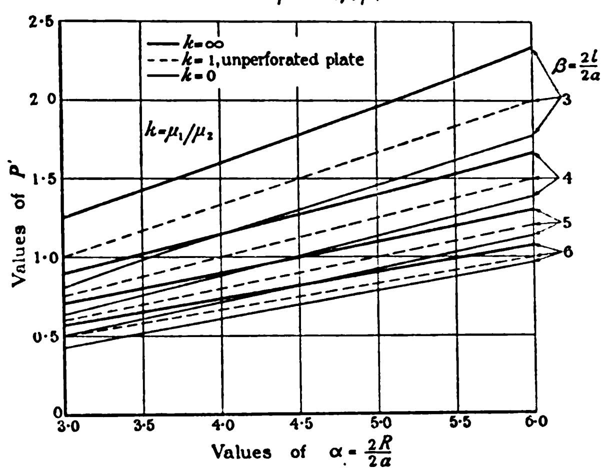

FIG. 5.—Geometric permeance curves for rectangular iron plate with close-fitting permeable plug of circular cross-section. The ordinates give the geometric permeance $\mathbf{P}'$ per cm axial length of the plate shown in Fig. 4.

μ_1 = permeability of plug.
μ_2 = permeability of plate.
$2l$ = length of plate in direction of flux.
$2R$ = central width of plate.
$2a$ = diameter of cylindrical plug.

All possible practical cases must be comprised between the following limits: (i) $k = \mu_1/\mu_2 = 0$, i.e. an infinitely permeable perforated mass with the hole filled by air or other magnetically indifferent medium for which $\mu_1 = 1$; and (ii) $k = \mu_1/\mu_2 = \infty$, i.e. a perforated mass of magnetically indifferent material plugged with infinitely permeable material. All other values of k lie between these limits, and a particular numerical example will be worked out later. For the present, Fig. 5 gives a series of curves showing $\mathbf{P}'$ as a function of α for various values of β with the limiting values of k just mentioned; the range of α and β is not extended below 3 as the validity of assuming the plate to be approximately rectangular then ceases to hold.

If a rectangular plate of breadth $2R$ and length $2l$ were unperforated the geometric permeance would be R/l, i.e. in terms of the hole in the perforated plate, α/β. Straight lines representing the permeance of the unplugged plate are shown in Fig. 5, whence it can be seen that the curves for $k = \infty$ and $k = 0$ lie above and below, respectively, the line for the unperforated plate, as would be expected. The influence of the plug on

the permeance becomes less as the perforated mass becomes larger, since, as is physically obvious, the local influence of the plug on the distribution of the field is then of much less importance, no matter what the relative permeabilities of mass and plug may be.

The effect of the plug is even more clearly shown by plotting the ratio of the permeance of the plugged mass to that of the unplugged plate, as has been done in

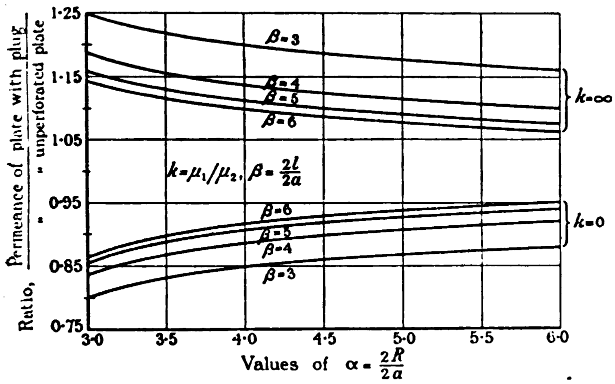

FIG. 6.—Curves showing the ratio of the permeance of a rectangular iron plate with a close-fitting plug to the permeance of the plate when unperforated.

μ_1 = permeability of plug.
μ_2 = permeability of plate.
$2l$ = length of plate in direction of flux.
$2R$ = central width of plate.
$2a$ = diameter of cylindrical plug.

Fig. 6. These curves show the proportion in which the permeance of a nearly rectangular plate is increased or diminished by plugging, plotted for the cases of $k = \infty$ and $k = 0$; all practical cases lie between these curves, probably nearer to the lower curves than to the upper.

(3) Perforated Mass with Loose-Fitting Plug.

The preceding solution differs in one particular from the conditions imposed by practical methods of con-

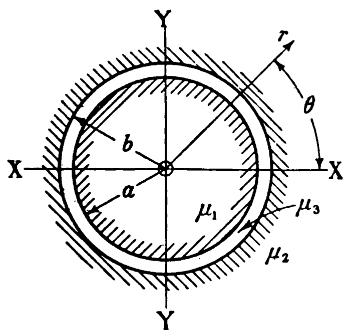

FIG. 7.—Co-ordinates for the field in a perforated mass with a loose-fitting circular cylindrical plug.

struction, in that the plug is assumed to fill completely the hole into which it is inserted. In the construction of a pole-core the steel piece is not necessarily a good machined fit in the hole; in the assembly of a transformer core the bolt is insulated from the laminæ by a tube or liner of paper interposed between bolt and laminated plates. An attempt will now be made to introduce some correction for the incomplete filling of the hole by the plug.

Consider an infinite mass of material of permeability μ_2 through which a hole of radius b has been drilled, a plug of radius a and permeability μ_1 being inserted concentrically therein, as in Fig. 7. The annular space between plug and walls of hole is supposed to contain material of permeability μ_3, usually magnetically inferior both to μ_1 and to μ_2. All other conditions of the problem are identical with those laid down in connection with Fig. 2. By arguments similar to those given in Section (2) appropriate general forms for the magnetic potentials in the three media will be

$$\Omega_1 = \sum_1^\infty A_n r^n \cos n\theta \quad . \quad . \quad . \quad . \quad (13)$$

$$\Omega_2 = H_0 r \cos\theta + \sum_1^\infty \frac{R_n}{r^n} \cos n\theta \quad . \quad . \quad (14)$$

$$\Omega_3 = \sum_1^\infty \left(C_n r^n + \frac{D_n}{r^n}\right) \cos n\theta \quad . \quad . \quad (15)$$

The coefficients can be found by noting that at the walls of the hole the tangential magnetic forces in the μ_2 and μ_3 media must be equal, and likewise the radial components of magnetic induction, i.e.

$$-\left(\frac{\partial\Omega_2}{r\partial\theta}\right)_{r=b} = -\left(\frac{\partial\Omega_3}{r\partial\theta}\right)_{r=b} \quad . \quad . \quad (16a)$$

$$-\mu_2\left(\frac{\partial\Omega_2}{\partial r}\right)_{r=b} = -\mu_3\left(\frac{\partial\Omega_3}{\partial r}\right)_{r=b} \quad . \quad . \quad (16b)$$

Again, at the surface of the plug similar relations for the tangential magnetic forces and radial magnetic inductions in the μ_1 and μ_3 media must hold, viz.

$$-\left(\frac{\partial\Omega_1}{r\partial\theta}\right)_{r=a} = -\left(\frac{\partial\Omega_3}{r\partial\theta}\right)_{r=a} \quad . \quad . \quad (16c)$$

$$-\mu_1\left(\frac{\partial\Omega_1}{\partial r}\right)_{r=a} = -\mu_3\left(\frac{\partial\Omega_3}{\partial r}\right)_{r=a} \quad . \quad (16d)$$

Substituting from equations (13), (14) and (15) in these boundary conditions gives the equations

$$H_0 \sin\theta + \sum_1^\infty n\frac{R_n}{b^{n+1}} \sin n\theta = \sum_1^\infty n\left(C_n b^{n-1} + \frac{D_n}{b^{n+1}}\right) \sin n\theta$$

$$\mu_2 H_0 \cos\theta - \mu_2 \sum_1^\infty n\frac{R_n}{b^{n+1}} \cos n\theta = \mu_3 \sum_1^\infty n\left(C_n b^{n-1} - \frac{D_n}{b^{n+1}}\right) \cos n\theta$$

$$\sum_1^\infty n A_n a^{n-1} \sin n\theta = \sum_1^\infty n\left(C_n a^{n-1} + \frac{D_n}{a^{n+1}}\right) \sin n\theta$$

$$\mu_1 \sum_1^\infty n A_n a^{n-1} \cos n\theta = \mu_3 \sum_1^\infty n\left(C_n a^{n-1} - \frac{D_n}{a^{n+1}}\right) \cos n\theta$$

Comparing coefficients we get:—

$$\left.\begin{aligned} R_n/b^{2n} &= C_n + (D_n/b^{2n}) \\ -\mu_2(R_n/b^{2n}) &= \mu_3 C_n - \mu_3(D_n/b^{2n}) \\ A_n &= C_n + (D_n/a^{2n}) \\ \mu_1 A_n &= \mu_3 C_n - \mu_3(D_n/a^{2n}). \end{aligned}\right\} \text{when } n > 1$$

$$\left.\begin{aligned} H_0 + (R_1/b^2) &= C_1 + (D_1/b^2) \\ \mu_2 H_0 - \mu_2(R_1/b^2) &= \mu_3 C_1 - \mu_3(D_1/b^2) \\ A_1 &= C_1 + (D_1/a^2) \\ \mu_1 A_1 &= \mu_3 C_1 - \mu_3(D_1/a^2) \end{aligned}\right\} \text{when } n = 1$$

It is not difficult to show that the first set of equations is satisfied by

$$A_n = C_n = D_n = R_n = 0.$$

Solving the second set of equations, if

$$c = \frac{2\mu_2 b^2}{a^2(\mu_2 - \mu_3)(\mu_1 - \mu_3) - b^2(\mu_2 + \mu_3)(\mu_1 + \mu_3)} \quad . \quad (17)$$

we have

$$A_1 = -2\mu_3 c H_0$$

$$R_1 = \frac{a^2(\mu_1 - \mu_3)(\mu_2 + \mu_3) - b^2(\mu_1 + \mu_3)(\mu_2 - \mu_3)}{2\mu_2} c H_0$$

$$C_1 = -(\mu_1 + \mu_3) c H_0$$

$$D_1 = a^2(\mu_1 - \mu_3) c H_0$$

Substituting these values in equations (13), (14) and (15) we get finally:—

$$\Omega_1 = -2\mu_3 c H_0 r \cos\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$\Omega_2 = H_0\left[r + \frac{a^2(\mu_1-\mu_3)(\mu_2+\mu_3) - b^2(\mu_1+\mu_3)(\mu_2-\mu_3)}{2\mu_2} \cdot \frac{c}{r}\right]\cos\theta \quad (19)$$

$$\Omega_3 = -cH_0[(\mu_1+\mu_3)r - (a^2/r)(\mu_1-\mu_3)]\cos\theta \quad . \quad . \quad (20)$$

Distribution of the field.—As in the preceding Section, applying the theory of orthogonal trajectories gives for the equations to the lines of induction

$$r\sin\theta = \text{constant} \quad . \quad . \quad . \quad . \quad (21)$$

in the plug;

$$\left[r - \frac{a^2(\mu_1-\mu_3)(\mu_2+\mu_3) - b^2(\mu_1+\mu_3)(\mu_2-\mu_3)}{2\mu_2} \cdot \frac{c}{r}\right]\sin\theta = \text{constant} \quad . \quad (22)$$

in the perforated mass; and

$$\left[(\mu_1 + \mu_3)r + \frac{a^2}{r}(\mu_1 - \mu_3)\right]\sin\theta = \text{constant} \quad . \quad (23)$$

in the annular space.*

The field has been plotted in Fig. 3 (*d*) for the case where $b = 1 \cdot 1a$, $\mu_1/\mu_2 = 2$, $\mu_3/\mu_2 = 0 \cdot 1$; that is to say, taking the annular space to be of air, for which $\mu_3 = 1$, this means that $\mu_2 = 10$ and $\mu_1 = 20$. It will be seen that the presence of the air space makes the concentration of the field unto the plug much less than when the space is absent, as in Fig. 3 (*a*). These values of μ_1 and μ_2 are much smaller than those which occur in a practical case; consequently the proportion of magnetic flux entering the plug is greater than would be found in practice where μ_1 and μ_2 are considerably larger in comparison with μ_3. For example, if no change be made other than that of taking $\mu_3/\mu_2 = 0 \cdot 01$, corresponding to $\mu_1 = 200$, $\mu_2 = 100$ for $\mu_3 = 1$, the field within the air space and plug becomes far too weak to enable it to be shown by tubes of induction of the strength used in drawing the diagrams in Fig. 3. In these more practical circumstances, and still more so as μ_3/μ_2 becomes smaller, i.e. as the iron parts increase in permeability relatively to that of the air space, the field in the main perforated mass becomes almost indistinguishable from that which is found by supposing the permeable plug completely removed. It follows, therefore, that when b/a is not too small, i.e. when there is a fairly considerable space of air or paper between pin and hole, as in the case of an insulated bolt passing through a transformer plate, the field can hardly differ appreciably from that treated in the preceding Section when $\mu_1/\mu_2 = 0$, i.e. an infinitely permeable plate with a hole of radius b in it. Thus in a highly permeable transformer plate the influence of bolt-holes can be allowed for by neglecting the presence of the bolt and calculating the permeance from the curves of Fig. 5 for $k = 0$.

In the case of a pole-core the pin or plug is not insulated from the main mass and the air space is therefore much smaller, being of the nature of a mechanical clearance. It is difficult to lay down any general principle governing this case since the permeance depends on so many factors. A particular numerical example will, however, enable important practical conclusions to be drawn.

Permeance of the field.—As in the preceding Section, the permeance of an approximately rectangular strip of breadth $2R$, length $2l$ and thickness 1 cm can be readily calculated from equations (18), (19) and (20). Calculating the magnetic induction across the Y axis in the plug, in the space, and in the main mass respectively, and determining therefrom the total flux Φ flowing in the plate, gives

$$\Phi = 2H_0\mu_2\left[R - \frac{a^2(\mu_1-\mu_3)(\mu_2+\mu_3) - b^2(\mu_1+\mu_3)(\mu_2-\mu_3)}{2\mu_2} \cdot \frac{c}{R}\right]$$

The difference of magnetic potential across the strip is, from equation (19),

$$\Omega = 2H_0\left[l + \frac{a^2(\mu_1-\mu_3)(\mu_2+\mu_3) - b^2(\mu_1+\mu_3)(\mu_2-\mu_3)}{2\mu_2} \cdot \frac{c}{l}\right]$$

Making use of equation (17), write

$$\frac{a^2(\mu_1 - \mu_3)(\mu_2 + \mu_3) - b^2(\mu_1 + \mu_3)(\mu_2 - \mu_3)}{a^2(\mu_1 - \mu_3)(\mu_2 - \mu_3) - b^2(\mu_1 + \mu_3)(\mu_2 + \mu_3)} = \gamma' \quad (24)$$

Then the permeance per cm axial length is

$$\mathbf{P}_1 = \frac{\Phi}{\Omega} = \mu_2 \frac{R - (b^2\gamma'/R)}{l + (b^2\gamma'/l)} = \mu_2 \mathbf{P}_1' \quad . \quad . \quad (25)$$

* The theory so far given, unrestricted as to the values of μ_1, μ_2 and μ_3, is precisely similar to the theory of a cylindrical magnetic screen. In the present problem μ_3 is small in comparison with μ_1 and μ_2 since the annular space contains air, paper or similar magnetically indifferent material, whilst the remainder of the field is occupied by permeable iron. In the screening problem the precise converse holds; μ_3 is large in comparison with μ_1 and μ_2, these being constants for air. The annular space of the present problem then becomes the wall of a permeable tube. For details of the screening problem see H. du Bois: "On Magnetic Screening," *Electrician*, 1898, vol. 40, pp. 218, 316, 511, 652 and 841, and vol. 41, p. 108.

Now write

$$\alpha' = \frac{\text{Central width of plate}}{\text{Diameter of hole}} = \frac{2R}{2b} \quad . \quad . \quad . \quad . \quad (26a)$$

$$\beta' = \frac{\text{Length of plate in direction of flux}}{\text{Diameter of hole}} = \frac{2l}{2b} \quad (26b)$$

Then
$$\mathbf{P}_1' = \frac{\alpha' - (\gamma'/\alpha')}{\beta' + (\gamma'/\beta')} \quad . \quad . \quad . \quad . \quad (27)$$

which is identical in form with equation (12). It is not possible to show the variation of $\mathbf{P}_1'$ in so simple a way as for $\mathbf{P}'$, since the quantity γ' contains the relative values of b/a, μ_1/μ_2 and μ_3/μ_2, i.e. three parameters. It is necessary therefore to take a specific numerical example to demonstrate the practical application of the results.

(4) Numerical Example.

Take the case of a rectangular plate pierced centrally by a hole, the length of the plate in the direction of the flux being four times the diameter of the hole. Take the breadth of the plate as four times the diameter of the hole and its thickness as 1 cm. These will represent fair practical proportions for a pole-core arranged for the insertion of a steel piece, or for the section of a transformer limb to be associated with one clamping bolt.

the hole, its radius a being given different values relatively to the radius b of the hole. Taking various values of b/a, γ' can be calculated from equation (24)

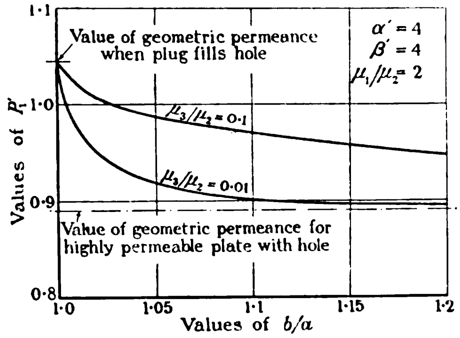

Fig. 8.—Geometric permeance of a rectangular iron plate with a loose-fitting circular cylindrical plug of permeable material.

μ_1 = permeability of plug.
μ_2 = permeability of plate.
μ_3 = permeability of space between plug and plate.
b = radius of hole.
a = radius of plug.
α' = (central width of plate)/(diameter of hole).
β' = (length of plate in direction of flux)/(diameter of hole).

for a given value of μ_3/μ_2. This has been done in the cases of $\mu_3/\mu_2 = 0{\cdot}1$ and $0{\cdot}01$, the resulting values of γ' for $b/a = 1{\cdot}01$, $1{\cdot}05$, $1{\cdot}1$ and $1{\cdot}2$ being calculated

Table 1.

μ_1/μ_2	∞	2	1	0·5	0·1	0·01	0
$\mathbf{P}'$	1·1334	1·0425	1·0000	0·9591	0·9027	0·8846	0·8823

Suppose first that the hole is completely filled with a permeable plug of permeability μ_1, that of the plate being μ_2. Then in equation (12), inserting $\alpha = \beta = 4$ gives for the geometric permeance of the plugged plate

$$\mathbf{P}' = \frac{4 - (\gamma/4)}{4 + (\gamma/4)}$$

Taking values of $k = \mu_1/\mu_2$ between ∞ and 0, calculating γ from equation (11c) and inserting the values in the above expression for $\mathbf{P}'$ enables the latter to be found. Table 1 shows some of the results.

This table shows at once that where the perforated plate is more than 10 times as permeable as the plug, i.e. when μ_1/μ_2 is less than $0{\cdot}1$, the permeance differs by less than 2 per cent from the value obtained on the assumption that no flux enters the plug at all, i.e. for $\mu_1/\mu_2 = 0$. A similar result can be shown to hold for other proportions of length and width of plate to size of plug than that chosen, the statement being more nearly true the wider and longer the plate becomes in comparison with the diameter of the plug.

Turning now to the case of a loose-fitting plug, take a plate of the same proportions as above, i.e. in equations (26a) and (26b) take $\alpha' = \beta' = 4$. Suppose a plug for which $\mu_1/\mu_2 = 2$ to be situated centrally in

and inserted in equation (27). The results are given in Table 2 and are plotted in Fig. 8.

Practical interest centres on two cases, (i) where the ratio b/a is nearly 1, the annular space being of the

Table 2.

b/a	$\mu_3/\mu_2 = 0{\cdot}1$	$\mu_3/\mu_2 = 0{\cdot}01$
	$\mathbf{P}_1'$	$\mathbf{P}_1'$
1·000	1·0425	1·0425
1·01	1·0160	0·9753
1·05	0·9891	0·9177
1·10	0·9686	0·9028
1·20	0·9465	0·8938
∞	0·9027	0·8846

nature of a mechanical clearance; and (ii) where the ratio b/a is of the order of $1{\cdot}2$ or so, where a definite liner is inserted as in the case of an insulated bolt passing through a transformer limb. In the former instance it is sufficiently accurate for design purposes

to suppose the clearance to be negligible and the hole to be totally filled by the plug, provided the clearance is less than 1 per cent of the hole radius. The permeance is then calculable from equation (12) with $a = b$, and the given value of μ_1/μ_2. In the second instance, if the plate has a high permeability exceeding, say, 100 times that of the annular air space, the permeance does not differ appreciably from the value obtained by assuming that no flux enters the hole at all whatever the permeability of the plug may be, taking $a = b$, $\mu_1/\mu_2 = \mu_3/\mu_2 = 0$, and using the curves of Fig. 5 for $k = 0$.

(5) Conclusion.

Experience shows that the modification of permeance given by the above theory for transformer limbs and pole-cores where the diameter of the hole is not greater than about one-third of the width of the perforated plate, agrees fairly well with what is found to occur in practice. There is one practical case of considerable importance in which the reduction of permeance predicted by the theory is much less than is actually found. This occurs with the pole-cores used in water-wheel generators, the plug having a diameter which may exceed three-quarters of the core width. Since the mere fact of perforating the core and filling the hole with a pin is insufficient to account for the reduced permeance it is well to point out the other facts, not included in the theory, which may contribute to the difference between theory and practice. (i) The plug is a large proportion of the width of the core and the theory is not, therefore, strictly applicable to perforations of such a large ratio. (ii) The plug is not concentric with the hole but is pulled down to the bottom thereof. (iii) The magnetic character of the core material in the narrow region left after punching the hole for the reception of the plug may be greatly impaired by the effect of local hardening due to the punching stresses. (iv) The permeability of the steel, especially in the narrow portion on either side of the hole, may be greatly reduced under the influence of the high tensile stress to which the pole-core laminations are subjected when the machine is running at the high peripheral speeds common in water-wheel generators. (v) The theory takes no account of the influence of the bolts which pass longitudinally down the core into the plug; as these bolts may be nearly as large as the plug itself their influence may be considerable. It would thus appear that such an extreme case as this, where the conditions of the theory are not fulfilled and the matter is complicated by numerous practical difficulties, can only be satisfactorily dealt with by exhaustive experimental investigation.

The results given in the paper have been worked out visualizing a magnetic problem. They apply, however, to the flow of electric current in a rectangular strip of metal perforated and plugged with a conducting pin, a conducting liner being interposed in the general case between the pin and strip. The permeabilities μ_1, μ_2, μ_3 are then to be taken as the conductivities of the media, $\mathbf{P}'$ and $\mathbf{P}_1'$ being the geometric conductances. In particular, the results of Section (2) for $k = 0$ enable the conductance of a strip with a hole through it to be found directly from the curves of Fig. 5.

In conclusion the author desires to thank Mr. S. Neville for valuable criticism and advice, and Professor S. Parker Smith for numerous practical suggestions.

POWER STATIONS AND THEIR EQUIPMENT.*

By W. M. SELVEY, Member.

The progress in power station design and equipment, much hindered by the war years, and by the following unsettled time, has now fairly resumed its former rate of rapid advancement. Progressing as it has in the past by waves, of which the crests represent departures towards increasing efficiency, and the troughs periods of consolidation, that is of increasing reliability, we are at the moment confronted with a steeply rising wave-front which may be termed the " High Steam Pressure " wave.

This departure, viewed in a detached attitude or, as our old English writers would have put it, viewed by the curious observer, is one of intense interest. The crests of the waves are always accompanied by increased capital costs—the cost of experimenting. The periods of consolidation show decreasing capital cost, the liquidation of experience. But the troughs are not quiescent, they have strong harmonic ripples.

Since to make a new departure involves increasing costs in one direction, it must be accompanied by some factor which diminishes cost. In power station plant this factor has hitherto been readily available; it may be termed the increase in the economic utilization of material. This obtains with increase in size and higher running speeds. But the harmonics are too important to be ignored. The advance once achieved on the larger scale, the benefits filter down almost proportionately to plant on the smaller scale. This done, during a period of consolidation, a fresh effort is necessary for advance.

Previous to the period under review the former steps of high superheat, low exhaust pressure, and increased ratio of blade speed to steam speed, which commenced with what were formerly large sets, had been very well digested in the smaller sizes. What had hung fire, so to speak, was steam-raising, and hence the protagonists of the " saurian " type of power station soon turned their attention to a development of boilers of a much larger size, and, almost incidentally, at first may it be said, to higher pressures. It will be realized that these simultaneous urges involved conflicting considerations. Thanks, however, to the special conditions and enterprise of the United States companies, every assistance was readily given to the development of size.

Simultaneously with size came the question of handling large quantities of fuel and increasing the temperature of combustion. Mechanical stokers were a little slow to respond to the new demands, and, moreover, engineers were instinctively feeling for a new outlook. The achievements of gas- and oil-firing were before them. For years they had dreamed of handling coal under similar combustion conditions. Diesel had dreamed of doing this direct in his earliest engine. Much good work had been done in cement processes. Fine grinding as applied to the manufacture of pigments was highly developed.

And then suddenly it came, and already the first ripple of the harmonic, the application of the " unit " system of coal pulverization to small-size boilers, is a " burning " question.

Moreover, stoker designers have felt the impetus and they have in large, and later in small, sizes considerably advanced. Another ripple arising out of the same matter bids fair to attain considerable amplitude. The smallest boilers, generally of the shell type, have given rise to Blake's now familiar expression, " Those black satanic mills." Power stations, with their partially brick-lined furnaces, showed how to solve the smoke problem. Alas, in this country the great majority are still of the old type. The advent of the large boiler, and its combustion chamber of rational size, has minimized the importance of the brickwork function. This is being effected naturally by the almost perfect mixing of " combustible " and " supporter," by the conserving effect of a large mass of flame, and by the space factor allowing time for the completion of the chemical action.

Hence we are now advancing to either a minimum amount of brickwork or partially cooled brickwork. The carrying out of the change is taking very interesting forms, both of tube walls and brick-covered tubes. Both old devices, coupled with the names of Yarrow and Bettington, are being resurrected for these purposes. Finally on this point a reaction on the boiler from the turbine has brought into prominence air heating.

The idea is very old both as regards producing better combustion and as regards recovering waste heat, but it has now a new aspect, that of the " regenerative " cycle. The heat in the gases leaving the boiler proper, i.e. the actual steam-raising surface, must now be kept in circulation by regeneration as it is rapidly becoming useless for feed-heating. This signifies really hot air. Even with stokers, boilers are now running with air at 400° to 500° F., but pulverized fuel provides a field for air much hotter than this in conjunction with very high-pressure boilers.

Fortunately, interchange of low-grade heat at atmospheric pressure between gases is much cheaper commercially and even easier than between gases and water under high pressure, and hence perhaps we foresee, in developments which are almost ripe, the disappearance of the mechanical stoker, the furnace brickwork, and the economizer all in one step. The boiler of the future will have small heating surface (the expensive high-pressure part), large superheaters, a large regenerator, powerful fans, and pulverizers.

It was perhaps fortunate, therefore, that this question of size came first, because if pressure had come first there would have been much hindrance due to installing a multiplicity of little boilers at high pressures which would have much delayed combustion progress. The

* A review of progress (see page 160). Reprints, in pamphlet form, price 1s. 6d. each, can be obtained from the Secretary of the Institution.

problem of size, however, was soon and ably solved, and this left the field free for a gradual increase in pressure, which at the present time is making rapid progress. This, however, is not quite all the story. The increase in pressure for an increase in efficiency would seem naturally to require as a corollary an increase in temperature. There, however, the work of previous pioneers, notably Ferranti, had called a halt. The providers of engineering materials were not yet prepared to supply steels which were equally strong, ductile, and permanent when rod-hot as when only warm. Now that the question has been raised much good work is being done. Hence, temporarily at any rate, this road of advance was diverted.

It has long been known that the Rankine cycle differed adversely from the Carnot cycle. Fortunate, indeed, has it been for mankind that the disadvantages hidden under this terse label were accompanied by much greater advantages to people with primitive raw materials. Nevertheless, the early engineering philosophers, many years ago, in inquiring into such matters, divulged a way of getting around the difference by employing a regenerative cycle. Again, by the process known as "reheating," it is possible more nearly to approach the Carnot fundamental. This, it is well to reapprehend from time to time, is to take in all the heat at the highest possible temperature, and effect the discard (probably a more correct expression than "losses") at the lowest possible temperature. Hence the "saurian" type of plant will hungrily appropriate into its constitution devices for reheating and bleeding, and find these the more to its liking the higher the initial steam pressure. This type has permanently appeared in France and the United States for ordinary and adequate commercial reasons. It is being fostered by political pressure in Germany and Great Britain, and consequently in both countries other considerations intervene. While 30 000-kW to 60 000-kW sets are becoming quite common in the States, and in France are being freely adopted, in England and elsewhere on the Continent the same impetus which commenced with 10 000-kW sets for capital stations is now expending itself in developing the largest output which at present can safely be given from a single alternator running at 3 000 r.p.m. At the moment this is 20 000 kW, but no difficulty is anticipated in increasing this to 25 000 kW. In fact the A.E.G. have constructed units for 32 000 kVA, and a British manufacturer has offered 35 000 kVA. It is too early to predict what the harmonics of this new departure will be. These will take several years yet to discover. One of them, which is applicable to all sizes of units, say, above 6 000 kW, is that of the slightly increased efficiency due to lower steam speeds. A previous ripple, that of the use of gearing, is still, however, progressing below this limit of 6 000 kW, and may, on the score of cheapness, come more prominently forward. A 10 000-kW unit has been constructed, and a 8 000-kW unit is under construction on the Continent.

A third, which is yet in its infancy but holds out some promise, is to add to the life of old stations by installing, for the steady part of the load, high-pressure (probably 600-800 lb.) boilers and discharge their output through back-pressure turbines to the main range.

As the conclusion of this essay, and before giving a brief résumé of plant particulars, it is necessary to point out the voluminous literature available on the subject. First there are the papers of the World Power Conference; then there has been an excellent series of articles in the principal English mechanical engineering journals. *World Power*, the organ of the B.E.A.M.A., has given a series of articles on typical power stations. The electrical Press has kept its readers well informed as to development. On the Continent the High-Pressure Steam Conference was held in the beginning of 1924; the discussions and the subsequent comments of the A.E.G. engineers are very instructive.

Finally, we may pay a well-earned tribute to the documents produced in the States and familiarly known in this country as the "Prime Movers Committee Reports" (National Electric Light Association).

Power Station Design.

This is a subject on which very little literature exists, and it was somehow reserved for Klingenberg to make it a substantive subject. Our early English writers have had their activities diverted into other channels. For some reason or other in this country anything "synthetic" is second-class matter; all the kudos is reserved for "analytic" work. It is a trait of the national character and is reflected in our policy, literature, and journals.

In most power stations in this country there can be no evidence of complete design, as their present state is the result of long accretion and alteration. New capital stations, however, are being built. Very fortunately their sites are being chosen for water facilities, as this generally carries with it ample land. After a generation of cramped extensions, more ample designs are possible.

The right-angled boiler-house design is still being developed in few but the more important cases, and this admits of much auxiliary gear and facilities being pleasingly housed in the space between two otherwise adjacent boiler houses. This design is, however, particularly adapted to small boiler units, and with the larger type of units coming into use the parallel design is necessary. Two boilers, and perhaps ultimately only one boiler, per turbine will be required. At present it involves placing special reheater boilers as close up to the engine room as possible.

When the implications of reheating and pulverized fuel have been fully absorbed, it seems possible that entirely new designs will emerge. It may then be that the buildings will be in three sections. A fuel-preparation section will contain the coal-handling and treatment plant. A power section may contain a number of turbo-boiler units, and a third section will be necessary for the switchgear.

Pulverizing plant at present runs to height and in the States it would almost seem that the mentality enforced by the sky-scraper of New York had been imported into power station designs, even when situated in lonely surroundings. It is suggested that

the condensation of plant achieved by plant manufacturers with generating machinery will later be supplemented by the power station designers who deal with steel work, buildings, and general civil work. This will result in less lofty buildings occupying a little more ground space and will lower prime cost.

The coal-handling plant for large stations is assuming a certain phase of standardization. The coal store is spanned by a travelling conveyor which can pick up at each end and deliver to any part of the store. Grab recovery from the store is also arranged. Wherever water-borne coal is available in addition to railway coal the apparatus must deal with barge or ship at one end and the coal unloaded by the usual truck tipplers at the other. On the larger sizes the old endless bucket conveyor is gradually being superseded by horizontal or inclined belts for traversing and grabs or automatic skips for hoisting. Over the bunkers either belt or travelling grab is employed. Many of such schemes embody automatic weighing apparatus.

The other big bulk "raw material," condensing water, has also received much attention. Tidal rivers present awkward problems. Travelling gravel and silt may seriously interfere with good conditions. However, the problem is still more acute in river water power schemes and valuable work is being done in overcoming these problems. Prolonged investigations have proved that merely muddy water is quite good water for condensing purposes, and a large station is now projected using Bristol Channel water, two smaller stations having used it for some time. Pumps are now generally installed of the vertical spindle type and with drowned suctions at minimum water level. Single pumps can deliver up to 1½ million gallons per hour. The design of a system using impure water calls for the elimination of settling pockets wherever occurring. What is required is to maintain the velocity uniformly throughout, and it is perhaps a coincidence that a reasonable velocity through condenser tubes for general efficiency is also a reasonable velocity for large conveying pipes.

Much progress has been made in screening plant. It has been realized that the earlier type of a travelling band in which the water went through both sides in series was not well conceived, because any detritus which escaped the water jets on the advance side was washed off on the trailing side into the system. Hence appeared the revolving-plate design, afterwards condensed into a hollow drum, and also the design where the travelling belt was still used, but the water was passed from both sides inwards and taken off laterally, or vice versa. In all of these later cases the foul side is always away from the screened water.

In busy rivers where much foul floating and water-logged detritus is caught on the screens, it has become quite a problem to dispose of the refuse. For a really large station an automatic transfer to a small destructor cell would seem to be indicated, with possibly a return of the ashes to the outgoing circulating water conveyed by the screen-cleansing water. These cleansing problems are absent where cooling towers are in use, and a fresh impetus to efficiency has been received by the use of these in an inland capital station, and by taking off the shackles as regards height. As in other phases, increase in size and ample land makes new departures profitable. Care has been necessary in providing for the expansion of the piping systems.

The movement of capital stations to river-side sites has brought out the fact that many of these are on uncertain alluvial deposit often water-logged, and extensive piling is required. This feature is international. In the States, with river-level rises greater than even the Severn tidal rises, this has given rise to difficult and expensive designs. If no question of coal unloading is a determining feature it is a matter for consideration as to whether a cheaper construction on the whole could not be maintained by bringing the water in open cuts or tunnels to some distance inland.

Very great progress has been made in civil engineering of late years in the use of powerful machinery for removing bulk material, and excavation is becoming only of relative importance compared with heavy piling and concrete rafting.

With larger stations the amount of railway sidings desirable is steadily increasing, and is a feature which is receiving growing attention. In the opinion of some engineers this is a main feature in going from 100 000-kW to 200 000-kW grouping in this country, having regard to railway and colliery conditions. Fortunately *pro tanto* the consumption of coal per unit is steadily decreasing, but against this there is the consideration that such stations must ultimately run as high-load-factor stations. The question may arise as to equipping such stations with trains of 20-ton trucks, especially if there is need to remove much ash from the site by rail.

Where adjacent land is available for ashes, telpher plant is proving very useful. Parallel development in coal-washing at the collieries will to some extent minimize this problem. The water-conveying system from ash-hoppers in town stations is incidentally providing a product which is finding increasing use in industry, and in some cases stations can actually sell all such material. In older stations, and especially in the States, the ashes contain such a high quantity of carbon that they could be rehandled in a modern destructor plant, entirely removing the carbon, and if in any quantity could be worked up into commercial material on the spot by a slab plant.

More than ever it can be realized that the future capital station should be surrounded by subsidiary industries and, although the time is not quite ripe, with the chemical refining works attached to a "low-temperature carbonization" process. It would seem that future legislation might well define some 300 to 600 acres around such a station as an "industrial area" relieved from the ordinary law of nuisance. It may, however, seem "Utopian" to look to legislation (new) for relief from legislation (old).

Boiler Plant.

While dealing later with the question of the utility of high pressure under the heading of turbines, a brief study of recent boilers may be of interest. So far plates of ordinary thickness with riveted joints have been found sufficient up to pressures of 300 lb. to

450 lb. (20 to 30 atmospheres). As the pressure rises the volume decreases and, with a constant steam volume per unit of disengaging surface, extra size does not seem to have involved priming. Perhaps, however, this is assisted by the adoption of the closed-circuit feed system which has resulted in a make-up almost negligible, in some cases as low as $\frac{1}{4}$ per cent. Such a small amount can easily be provided by a system of evaporation by live steam. Apparently also the simple system of expanding tubes into plates and headers has been equally successful.

With superheaters, however, the tendency in the States is to make this a speciality supplied by a separate company to the boiler maker, and there is a growing use of the ball-and-cone metal-to-metal joint as adopted in the Schmidt type. With the headers, bolts and nuts left unlagged or lightly lagged, the tube may be adapted to much higher temperatures, especially with new materials, which are gradually becoming available. The use of a material to stand strain and temperature at the same time is, as a general principle, to be avoided wherever possible. This will be referred to later in connection with turbines.

For reasons which have already been touched on, overhead heating surface is now in large boilers being supplemented with furnace side wall and bottom heating surface. The initial arrangements were a little casual, but the principle is now finding acceptance of making such heating surface into a proper circulating system in parallel rather than in series with the remainder of the heating surface. This principle had already received some acceptance in the double-circulation type of horizontal-tube boiler, wherein the two bottom rows of tubes had their own headers and discharged straight to the main drum. Considerable developments are expected in this connection, and although the outward resemblance may be superficial there will be underlying the design of future boilers much that will remind the engineer of the pioneer work of Bettington. There will, however, be important differences.

Out of the much higher pressures there will also arise demands for solid forged drums of large diameter. At present, forge-masters, both in Britain and in Germany, are seriously tackling this problem, where it has the added interest of being associated with the problem of catalysis under high pressure and temperature for the synthetic production of mineral oil direct from coal, and for other endothermic reactions such as cracking for the production of petrol from crude oil. One British boiler manufacturer has done excellent work in this direction, producing drums 40 feet long, 42 inches internal diameter, and 4 inches thick. The 1 200-lb. pressure boiler at the new Boston station has a solid forged drum 34 ft. long, 4 ft. internal diameter and walls $4\frac{1}{2}$ in. thick (Patchell). The whole problem of large forgings is calling generally for a fresh step forward in this country, and in this should be included not only boiler drums but also turbo-alternator rotors and discs and piping for larger diameters. While on the question of materials this addition to the use of solid drawn piping should lead to the abolition of all pipe flanges for high pressure, the ends of the pipes being socketed and the whole welded up after erection. Good progress is being made in the States in this direction, and for the small amount of large-diameter piping foreshadowed in the "one turbine—one boiler with reheating" unit it may become standard.

At the present time much interest is displayed in cellular brickwork furnace construction. With the intermediate size of boiler, some brickwork must remain for a long while. The drawing of combustion air through such cells by unit fans and using it directly through forced-draught stokers, combined with the use of newer refractory materials of clay, bauxite, magnesite, or electric furnace products, may be a first harmonic applicable to existing boilers which already have ample economizers installed.

With larger boilers, and especially with boilers using pulverized fuel with hot air, the brickwork problem will gradually become secondary compared with the ash-disposal problem.

The progress made with clinker grinders, and at the same time with various water-trough systems, should ultimately lead to an abolition entirely of the boiler basement and at one stroke reduce the height of the boiler house some 16 ft. to 20 ft., with consequent reduction of what is really overhead cost. At the moment no use seems to be found for the dust from pulverized-fuel combustion which is collectable from all passes in the boiler, and also from the latest and highly desirable development of centrifugal dust extractors at the stack. Considerable progress has been made in the use of machine soot-blowers, and published curves of back-end temperature give a clear idea of their value. All is tending to eliminate rough labour in quantity and replace it by skilled attendance and repair. This will doubtless be followed up in a period of consolidation by close scrutiny of repairs, which are at present a considerable item in the economic balance sheet.

If we are to treat the pulverizing plant as part of the boiler plant, it is advisable here to comment on British coal conditions. The British customer, with his majority of shell-type boilers, has been utterly spoilt, and it was a serious embarrassment to this country during the war years to find that many boiler plants could only be kept going by the use of washed treble nuts. It was also an almost equal embarrassment to find so many consumers fully persuaded that they were in like case, which illusion had to be exploded. It is remarkable to find, however, that in many cases it was only suppressed and has recrudesced even in some large power stations. Great pressure is to-day being put on collieries to increase their supplies of washed and graded fuel. Many American stations are adapted to take "run of mine" coal, and for pulverizing work this may be a positive advantage as it gives a product with lower average moisture content. British products for a long time will, however, be divided into best large, nuts, and good and poor slacks, washed and unwashed but often very damp. Hence predrying is going to be a much more serious matter in this country, where the introduction of this new method must be based on these tail-end coals. No doubt, with the unit system and small boilers, apparatus will be found to deal satisfactorily within

certain limits as to coal sources and moisture contents, but for the general problem predrying is still in the development stage. It can be done satisfactorily, but the apparatus is expensive and large.

It is interesting to note that in the new station at Rummelsburg for Berlin, the drying of fuel is to be effected by bled steam from a "feed water heater turbine" of 10 000 kW.

Grinding plant is in a much more satisfactory position and the period of time for replacement of wearing parts is increasing. Greater attention to detail has made the plants more dust-proof, but perhaps it is too much at present to ask the designers to make them noiseless, although promises as to this can even now be obtained.

There is nothing to hand at the present on the subject of burners discharging upwards, whilst information as to burners discharging downwards and horizontally is not new. With the abolition of much furnace brickwork positive supply of secondary air is increasing, and this will lead to flame-shortening and greater liberation of heat per cubic foot of combustion space. Progress in this direction is likely to be rapid.

The progress in stoker plants is also worthy of mention. Compartment-type forced-draught stokers are replacing totally-enclosed chain grates, and with these hotter air can safely be passed now only through the upper coal-carrying side of the belt. This leaves the grate on its return journey open to any form of cooling which may be devised, such as water cooling. With some types of British coal this will result in burning out the volatile too early in the grate, whilst with other types of gassy coal excessive temperatures will be developed, and forced cooling of the metal in some way will be essential.

The suspended type of arch now admits of very wide single stokers which, considering their duty, are worthy of a great tribute to stoker designers.

In the attempt to save the last trace of heat losses, boiler forced-draught fans are now sometimes arranged to draw hot air from the boiler room, thus recovering some of the heat losses lumped under the term "radiation." The system of drawing in the alternator cooling air for the same purpose is now obsolete owing to the advent of alternator closed-circuit coolers. Traversing shutes for mixing the coal in the stoker hoppers have been adopted as good practice.

Turbines.

As a preliminary to the turbine question it is proposed to quote a considered opinion by the A.E.G. engineers as a summing up of the discussion at the High Pressure Steam Conference of 1924.

"While theoretically the heat consumption for condensing machines shows a decreasing tendency up to 100 atmospheres (1 500 lb., taking atmosphere = 15 lb. instead of 14·7 lb.) any increase of the pressure over 60 atmospheres (750 lb.) has no practical advantages in ordinary condenser power stations from a thermo-technical point of view.

"The most economic steam pressure for condenser power stations is generally below 60 atmospheres because the thermal gains are counteracted by the greater capital costs at the higher pressures, principally on account of the increased cost of boiler equipment. The present state of boiler construction indicates that, as shown by calculation, the most economical boiler pressure for a condenser station is about 30 to 35 atmospheres (450 lb. to 525 lb.).

"The use of high steam pressure in large power stations has become possible because the high-pressure part of the turbine has been successfully arranged to work at least as economically as the low-pressure part. Until a short time ago the high-pressure part worked at a lower economy. This was permissible because with pressures of about 12 to 15 atmospheres (180 to 225 lb.) only a small part of the heat drop took place in the high-pressure part. . . .

"Turbine manufacturers are now in a position to build turbines for the highest pressures whose efficiency approaches that of the best machines that work with normal pressures (180 to 225 lb.). . . .

"With pressures over 35 atmospheres (525 lb.) an intermediate superheating of the steam in the middle stages is necessary to reduce moisture in the low-pressure stages.

"Tests are being undertaken at 60 atmospheres (900 lb.) in Germany and Sweden, at 84 atmospheres (1 260 lb.) in the United States."

We might add "at 1 500 and 3 000 lb. in England," referring to the Benson boiler, further experiments with which it is understood are to be transferred to Germany. Also that there are Babcock boilers working in Belgium at 800 lb. per sq. in. supplying a high-pressure turbine which exhausts at a pressure of 350 lb. into an existing steam main serving other turbines at this pressure.

We might also mention the 1 200-lb.-pressure boiler at the Boston new station, which supplies steam at 1 000 lb. pressure and 700° F. total temperature to a 2 500-kW turbine, which discharges for reheating at 375 lb. back pressure (Patchell).

There is also the curious system of Löffler in which the heating surface is entirely tubular and the steam generated is circulated through an external drum and superheater by a pump. This system is being installed on a small scale in Vienna for 1 500 to 1 700 lb. pressure and 750° F. to 900° F. total temperature. A 18 000-kW plant is stated to be under construction for collieries in Moravia.

In this condensed statement there is much matter for discussion by experts, but it is on the whole a fair résumé of the facts as they appear at the moment.

First as to the theoretical side, it is a matter for congratulation that British turbine manufacturers have been able to arrange for Prof. Callendar to extend his well-known steam tables to meet these higher conditions, and that they are in touch with our American

friends in the same matter. A theoretical essay on the same subject has appeared in the *Journal*.*

It has been generally noted that the gains yet to be made were, compared with previous advances, rather on the small side. Since that time more attention has been paid to the fact that the practical value of superheat is nearly double that of the diagram value, but on the other hand closer attention has emphasized that the reheating must be done without appreciable pressure drop. Because of this the second turbine taking the reheated steam cannot have its own governor, and the volume of steam entrained in the re-superheater is enough to cause a turbine to run up beyond emergency speed if tripped when fully loaded. The present solution is rapid vacuum breaking, but we think others will emerge. The reheating pressure is too low for this system, and already a scheme is being constructed whereby a small back-pressure turbine operates direct on the boiler and governing is done past the reheat at a high pressure still sufficient to give 80 per cent of the output. The alternators being solidly interlocked, the small turbine cannot run away, and in any case it can still be under the operation of a full-way emergency trip valve.

The conditions of high efficiency referred to no doubt signify the abolition of the "Curtis" wheel, but we should like to point out that the high-pressure end of a large reaction machine has always been of high efficiency, especially since the introduction of "end-tightening." The new Chicago machine for 525 lb. pressure is a case in point. With the advent of rustless steel blades for this work, as now used at Heaton, combined with their method of manufacture, it is quite safe to assume that English manufacturers are also in a like position. We also recall Ferranti's pioneer work with nickel-coated welded-on blades which were used in a successful turbine at Sheffield several years before the war. Moreover, an important large machine of the impulse type using forged stainless-steel blades is under construction for a municipal power station.

A Continental firm claims, after an investigation by Stodola, to have still further improved the efficiency of reaction blading, and it would seem that a prediction made in the *Journal* so long ago as 1904 † as to turbines having an efficiency of 85 per cent is likely to be realized shortly. We are reminded by this that in certain other of Ferranti's early experimental work a small non-condensing reaction element was run at varying speed to discover the optimum of efficiency, and a result of 90 per cent was believed to have been obtained.

The question of casing, however, does require some consideration, as the small high-pressure turbine casing has to carry pressure and temperature and the intermediate-pressure casing has also full temperature in the newest proposals. (Also in emergency, if on a separate shaft, a direct steam supply.) Proposals are being made to investigate any possible growth of casing steels under these high temperatures.

The question of providing a material to stand both stress and high temperature at the same time has long been considered. At last as a result of research by French engineers a material is available which, according to Hadfield, is "not only non-scaling at temperatures up to or even exceeding 1 050° C., but is also resistant to the action of the sulphurous products of combustion, and further this steel also possesses remarkably high strength and tenacity at even up to about 900° C. at which, as is well known, the strength of ordinary steel is practically negligible."

Thus a new door is opened to increasing total temperature.

In Ferranti's pioneer work, which was with very hot steam, the high-pressure casing was double, and English manufacturers are now considering the application of a lower-pressure jacketed casing, particulars of which cannot yet be published. In fact, many of the most interesting proposals both for boilers and turbines must remain confidential at present.

The introduction of one bleeder heater is now becoming standard even in moderate sizes of units, and where re-superheating is employed one interheat is at present all that is proposed.

Reference may be made to the theoretical essay already mentioned. No clear-cut figure can be given for the value of one or more interheats as the selection of the data is arbitrary. It may be considered as being around the value of 6 per cent. With regard to successive bleedings the matter is also complicated by boiler conditions.

Thielsch (A.E.G.), however, in a very able paper elaborating the general conclusions already given, states as follows :—

Values applicable to a 16 000-kW turbine or larger.

No. of bleeding points	1	2	3	4	5	6	8	10
Heat saving, per cent	4·9	6·4	7·1	7·7	8·1	8·4	8·8	9·1

His comment is that there is no considerable advantage in using more than three stages.

The matter is further complicated in British and American practice by apparatus for taking up steam from feed pumps, air pumps, glands, etc., in series with the turbine bleeders proper, and probably one bleeder heater is nearly enough for most moderate-size plants in this country.

In the States, however, in what are there termed "heat balance" stations where no flue-gas economizers are employed, this system is pushed to its limits, and results of 13 000 to 14 000 B.Th.U. per kilowatt-hour are claimed over a month's run.

It is very interesting to note Dr. Thielsch's conclusion as to what can be accomplished as a whole, using to the fullest advantage the schemes which have been outlined. Perhaps his comment on the table which is reproduced on page 491 provides a pointer. It is: "This proves that in modern power stations which are built in accordance with the principles stated above, a thermal utilization very nearly equal to that possible with Diesel engines can be realized in practice." However that may be, there are other considerations, and the results of Barton and Carville B, published in

* W. M. Selvey: *Journal I.E.E.*, 1920, vol. 58, p. 31.
† C. H. Merz and W. McLellan: *ibid.*, 1904, vol. 33, p. 696.

Steam pressure	15 225	35 525	100 atmospheres 1 500 lb. per sq. in.
Heat consumption	3 400 13 500	3 050 12 100	2 800 kg cals. per kWh 11 100 B.Th.U. per kWh
Thermal efficiency	25·2 %	28·2 %	30·6 %

the Electricity Commissioners' returns and the recently published results from Hell Gate, show that these figures are being approached without fully adopting all that is now open in the way of thermodynamic advance. The results of the new Chicago station at 525 lb. and with 50 000–60 000-kW units are keenly awaited.

In many cases the older stations, which were constructed at times of lower prices, can well hold their own when it comes to total generating costs, including capital charges, but since high prices are now becoming stabilized, this cannot be used as an argument for hesitating to adopt the more elaborate efficiency cycles in complete new stations.

The impulse type of turbine has now taken a fresh step forward by adopting features of many wheels, low steam velocity, high velocity ratio, and complete peripheral admission. As far as the high-pressure end is concerned, coupling efficiencies of over 80 per cent are credibly claimed. This had been due, in this country at any rate, to the results published by the Steam Nozzles Research Committee of the Institution of Mechanical Engineers. These showed conclusively that the best results could be obtained by a moderate pressure-drop per stage. The name of "Erste-Brunner" is popularly associated with this many-stage design, but hardly with justice, as a reaction from extremely high peripheral velocities had set in previous to this phase, and most English and American manufacturers were already moving in this direction when the Committee's results gave added impetus to the movement by providing additional good reasons for the reaction.

Hybrid designs with low velocities at the high-pressure end and high velocities at the low-pressure end are still being prepared for single-cylinder machines, with calculated efficiencies but little lower than the best.

Some Continental designs are very similar in appearance to Rateau's first two-casing turbine made by Sutter-Harlé so many years ago. This design, though arrived at for other reasons, lends itself well to the increased pressure, temperature, reheating, and bleeding cycles.

When pushed to its logical conclusion, one Continental design shows 4 casings and extends 100 ft. There are no engine-rooms in this country as wide as this. The solution which has long been in vogue in the American Westinghouse designs, and which will probably increasingly be adopted in large units, is that of using more than one shaft line with electrically interlocked alternators as at Barking.

The double-revolution turbine continues to progress and a 10 000-kW unit is under construction. This size of plant is similar to the 5 000-kW size, in that the last stage has single-revolution radial blading, giving double flow of steam for the last expansion.

Coming to the exhaust end, while impulse turbines have for a time adhered to one casing with multiple exhaust wheels, including the Baumann exhaust, the advent of the multiple-wheel design calls for two casings, and in Continental designs a plain double-flow low-pressure design is employed. The advent of 3 000-r.p.m. machines has led to the abandonment of the $D/5$ rule, and an important development is that of tapering, shouldering and even twisting blades.

This latter development makes a blade similar in principle to a propeller blade. Shrouding has also received attention and is being specially lightened between blades, and in some cases chrome steel is employed for strength. The vibration trouble of blades has also resulted in special lacing and stiffening. Disc vibration, which appeared suddenly during the war, has now become both a theoretical (Stodola, Lamb and Southwell) and practical (Chittenden and the late Wilfred Campbell) subject, the synchronous period of transverse vibration being tested out before assembling. Discs are also overspeeded in a wheel-pit before mounting. As before mentioned, the question of large forgings has been reinvestigated because of a phenomenal flaw, which wrecked a well-known machine and which could not have been previously discovered by methods then in vogue.

The multiple-casing design has one important feature, that of limitation of the size of forging. Almost everywhere at the present time there is a certain unrest on the question of large forgings for high revolution work, especially where temperature gradients are present simultaneously. Hence makers of prime movers are devising elaborate methods of scrutinizing forgings, and it is not by any means a foregone conclusion that a forging will be passed. Sometimes flaws are not discovered until the final machining has been done.

A notable 20 000-kW machine which has just been set to work has been designed to take advantage of the "low velocity—many-wheels" scheme. The high-pressure rotor has been turned out of the solid forging, only the blades having to be added. By this method, combined with trepanning, only a few inches of metal in a large forging remain unexamined. The above machine is also of special interest in that it has a low-pressure double-flow reaction bladed end in tandem. We may also refer to another slightly smaller tandem-cylinder machine which has recently been put into service. This embodies an impulse high-pressure cylinder with the "many-stage" low-velocity impulse wheels followed by a few rows of reaction blading and a double-flow reaction low-pressure cylinder. The actual rotor forgings in this instance are also of small diameter, all discs in the high-pressure cylinder being shrunk on to the rotor, and in the low-pressure cylinder where the reaction blading is

fitted a disc construction is similarly used. In this particular machine a novel method has been devised allowing free expansion, whilst preserving alignment. Most manufacturers have adopted exploring apparatus to sight any flaw which crosses the bore of the trepanned portion, and one firm is developing electrical methods for completely exploring the whole forging, particulars of which are not yet available. These methods are of equal assistance in dealing with alternator rotors.

To present fairly both sides of the question the following remarks are offered by one of the prominent forge-masters :—

> "Some designs of turbine forgings, however, are causing considerable uneasiness in the minds of British forge-masters who appreciate the dangers of internal stresses due to rapid variations in diameter, combined with the segregation which is bound to exist in all ingots. The present tendency is to increase the size of turbine forgings, and designers generally appear to be ignoring the fact that the greater the mass of liquid steel in the ingot mould, the longer it takes for the ingot to cool down, with a consequent increase of segregation, crystalline structure, and internal stresses. Further, from the anxiety in the minds of the designers to have a reasonable margin of safety, specifications are stiffened up so much that the figures asked for cannot be given without hardening and tempering. This operation in a solid mass with quick changes in diameter presents a very real danger. In heating and cooling during treatment operations it is impossible, whatever precautions are taken, for the whole shaft to be kept at a uniform temperature, with the result that internal stresses must inevitably be left in the forging. It should always be in the designer's mind, therefore, to avoid sudden changes of section, and, wherever practicable, to design heavily stressed turbine forgings with as large a hole as possible along the axis."

From what has been said in the previous paragraph on two-cylinder machines, it would appear, however, that designers are not by any means ignoring the facts.

Condensers.

Although condensers are not subjected to high pressures and temperatures, the physics and economics of their functions are equally fascinating to the narrower circle interested. Progress in this direction is still very rapid. With the advent of the steam ejector air-pump, now almost universal, the condenser as then constructed completely outran the turbine.

Designers began then to fit smaller condensers made, so to speak, to the same drawings. This has been seen to be a mistake as the most important economic factor, pressure-drop on the steam side, was misapprehended. Now these steps are being retraced and it is being realized that there is a certain consideration which takes the form of an optimum value of the percentage volume occupied by tubes in a given condenser shell, counting this from the turbine flange.

The effect of increased water velocity has been explored and discounted by pumping loss settling down to between 6 and 8 ft. per sec. through the tubes. If anything, the tendency is at present to keep down the velocity. Theoretically the ideal condenser has its tubes arranged only two or three deep with very large width. This is discounted by the abnormal shell necessary and the latest design, passing through the boat-shaped stage, is towards either an accordion type, or squirrel-cage-type arrangement of tubes. Both designs are directed to short steam paths, but the accordion type lends itself to the preservation of steam velocities, and the small recovery of pressure from velocity seems from experiments on a small scale greatly to increase the condensation rate. On a larger scale a remodelling of one of the Genevilliers condensers on these lines has produced remarkable improvement (Rauber). It is easy to see that a shallow condenser is less affected by tube fouling than a deep one.

Most engineers are now familiar with this station and yet in its short life there has already been opportunity to make three separate advances. Both the accordion and squirrel-cage types are being developed in England in conjunction with the American and French originators. From the outside engineer's point of view, the advance will be summed up by viewing it as condensers with somewhat smaller shells and very many fewer tubes.

Twin condensers for the largest sizes are becoming increasingly common, and have the advantage of lesser depth than one large one as well as some slight advantage of sectional cleaning. We believe, however, that modern methods will generally be developed of cleaning without the labour of brushing tubes by hand labour.

Condensation rates to-day can confidently be taken on a 450 B.Th.U. per sq. ft. per hour per 1 deg. F. logarithmic mean difference between water temperature and "inlet" steam temperature. Half as much again can be ensured if special methods are adopted, and it would seem possible to look forward to double this rate in the future. Combining modern air-tightness with ample air-pump capacity, condensate temperatures with the new designs will only be a degree or so below steam inlet temperatures.

The demands of closed-circuit and heat-balance systems have resulted in the adoption of two-stage air-pumps, with a combined surface intercooler and condensate heater, which replaces the system of a jet intercondenser. All the steam heat is recovered. It is realized that compression ratio is the determining factor in steam economy, and in one important station to meet a difficult specification three-stage pumps were fitted to 25 000-kW units. Since then, the system having proved economical, it has been supplied for still larger units.

Where the circulating water to the unit is supplied by its own isolated auxiliary, it is now practically standard practice to have two circulating pumps each having a capacity of 60–75 per cent of the total water required. Generally one of these pumps is steam-driven, and sometimes a pump is arranged to be either steam- or motor-driven alternatively. The busbar system of supply from the common pump-house is, however, generally preferred.

Alternators.

Much quiet progress has been made in alternator design. Rotors of 60 000 kW at 1 800 r.p.m. have been started up, and 25 per cent larger are offered. 25 000-kVA rotors are running very successfully at 3 000 r.p.m. in England, and offers have been made up to 35 000 kVA at the same speed. It is stated that units have been constructed on the Continent of 32 000 kVA at 3 000 r.p.m. and of 62 500 kVA at 1 500 r.p.m. In America a 80 000-kVA unit at 1 200 r.p.m. is under construction. To appreciate this, reference should be made to Baumann's papers.*

Only a few points can be touched on. Ventilation is one of the most interesting. The air is now specially guided over end-turns and also guided to all parts of the rotor gap. Some rotors are made up solid, depending entirely on peripheral cooling. The higher resulting temperature is permissible because of greatly improved shop methods of coil insulating by hot pressing. Other designs show great ingenuity in getting air along ducts in close proximity to rotor coils. Most designs are machined from the solid, that is with solid teeth closed after winding by partially magnetic wedges; others have laminated teeth riveted while under hydraulic pressure and carried in dovetail slots.

Whilst shrunk-on end-caps for rotors are still generally used, in one particular design great care is exercised, in this the most difficult part of the whole rotor (the end-turns), to wire-wrap them on to the shaft with known and recorded tension. It should be stated that considerable advance has been made by the steel-makers in producing material suitable for end-caps, combining high yield-points with good elastic and even non-magnetic properties.

Modern developments call for flexible cable or laminated copper for coil-turns, and this is now generally used, being pressed into shape and also transposed within the slots, all to minimize copper eddy-current losses.

Stator end-windings still persist in their three forms, and advocates of each type appear to have arrived at satisfactory bracing.

End-clamping stator plates are also devised to render through coupling bolts unnecessary.

An interesting development is the use of a non-magnetic cast iron with high specific resistance for these end frames.

The feature which has recently so rapidly become standard is that of closed-circuit air coolers, thus superseding both dry and wet air filters. Their advantages are too well known to need recapitulation in full; absence of dirt, moisture, limited supply of oxygen, shorter shaft when employed with external fan, and more efficient fan, are a few of these.

In all cases these must be fed in some part by the coolest convenient source of inexpensive water. It can, however, be arranged that the condensate shall participate in the first stage of cooling when the incident air is at its maximum temperature. With the various sources of heat available for feed-heating and with the practical disappearance of condenser loss this scheme is more applicable to river water than to cooling-tower stations.

* *Journal I.E.E.*, 1912, vol. 48, p. 768; also 1921, vol. 59, p. 565.

Buried temperature detectors have been slowly introduced for stator coils and iron, and are now recommended as a standard practice for machines above 5 000 kW. Records which enable rotor voltage to be divided by rotor current on an instrument which does this may shortly become a common means of watching rotor temperature by change of resistance.

In addition to the magnetically-closed slots, which are of importance with machines running on high-capacity systems, another feature is of considerable interest. Some designs provide for building what is really a squirrel-cage winding into the rotor slots. This acts as an additional damping winding, and protects the rotor in case of short-circuit, and with out-of-balance currents in the stator.

Designers are more than ever convinced of the value of inherent reactance in the alternator. They now incorporate between 15 and 20 per cent and they expect to be able to increase this in the larger sizes. We should recognize the merits of the automatic voltage regulators in making this possible. Whilst there is no difficulty in winding most machines to-day for 11 000 volts, the tendency where step-up transformers are employed is to revert to 6 600 volts. There appears to be no development yet along the lines pointed out by Welbourn * of winding for higher voltages.

Power Station Auxiliaries.

Whilst much discussion has taken place on this subject there is not much new matter. There is perhaps an increasing proportion of electrical auxiliaries supplied

(*a*) From low-tension house turbine alternator in parallel with and/or

(*b*) Unit transformers or unit winding on step-up transformers in parallel with and/or

(*c*) Transformer across main e.h.t. busbars.

A variation of the house-turbine or unit-transformer scheme is to add a low-tension alternator or d.c. generator for the auxiliary service in tandem with the main alternator, i.e. on a shaft extension.

Of these methods, two as far as possible independent sources are considered to be a minimum provision. It is now generally considered advisable to use storage batteries for stand-by emergency lighting and for operating the switchgear trip-coils.

Switchgear.

Switchgear in large sizes and for high tension contains so many unknowns that it is difficult to know whether four lines of development now going on are all simultaneously worthy of being called "progress." Research and experience are gradually eliminating certain of the unknowns and the importance of the switchroom is now being realized.

Schools of thought receiving almost equal support are:—

(1) The all-metal-clad compound-filled (and/or oil) system.

(2) The moulded stone cubicle system.

(3) The air-divided porcelain-insulated system.

(4) Cubicle "phase isolated" system.

* *I.M.E.A. Proceedings*, 1919, p. 78.

The largest metal-clad switches have developed duplicate busbars and separated phases into individual tanks, in some cases with duplicate switching.

The moulded-stone-cubicle advocates are beginning to coquette with mica or tape insulation over all live parts, and composite designs are also proposed.

The "phase-isolation" designers are going almost to extravagances in pursuing their ideals. In this country the first types can be seen in their developed stage at Dalmarnock, Nechells and Barking, and the second at Barton and Salford. The third is perhaps best seen at Gennevilliers, but for the latest development of the fourth type we must go to the States (Hell Gate, Calumet, etc.).

All types, without knowing definitely (if such a matter can ever be known) what their switches will stand up to, have steadily increased in size of units. Such is the state of the art that no one desires wantonly to produce a short-circuit providing an adequate test, and whilst tests are gradually being carried out on single generators, which are on the whole coming out well, yet the use of, first, busbar reactance, and later of feeder and interconnector reactance, is still is some quarters regarded as essential on large systems. The inherent reactance of a single machine protects the machine, but given a sufficient number of machines the switchgear is still unprotected, unless reactance is suitably diffused through the system for its own protection and the switchgear is sectionalized.

Much good work has been done to protect the operator and prevent accidental contact when cleaning, or during wrong operation. The engineering and workshop practice is getting highly developed. Larger single porcelain insulators are being satisfactorily obtained, as well as moulded insulation tubes. Condenser type and oil-filled terminals are all contributing their quota to satisfactory operating gear, but at present it would seem impossible to nail down any one specification and say "thus." The use of metal-clad gear for auxiliary switching is becoming general, and only in a few instances when the designer has some particular leaning to direct-current auxiliaries will be found the old elaborate polished slate and burnished copper type of board.

It is tacitly implied in the foregoing that wherever the amount of power to be dealt with is large the main switchgear will be dealing with the current from the step-up transformer, and that the transformer for this purpose may be practically considered to be an extension of the generator.

General.

A matter in which considerable progress is being made is that of station instruments. Electrical boiler-level remote indicators are now available and seem to afford a reliable indication at firing floor-level of the water in the drum. In view of the severe strain on gauge glasses at high pressures and temperatures, such an addition is welcome.

Temperature, draught, and CO_2 indicators are becoming of a more robust design suitable for engineering works. Instruments are now available for recording the presence of combustible gases in the flue gases. Steam meters with electrical indicators, and integrators with compensated voltage effect are finding gradual acceptance. A recent development of this, the combination of a steam meter with a water meter, enables steam consumption rates to be observed directly.

The principle of the "Dionic" water tester has now been applied for indicating and recording the conductivity of the condensate for watching condenser leakage. Chlorinating gear has been successfully applied for keeping down marine growth in water pipes. Closed-circuit systems for condensate have been more conveniently opened into surge tanks, steam-sealed, which device prevents the entrance of air, and incidentally still admits of "V" notch recording.

Where large make-up is required multi-effect evaporators are being installed. For smaller quantities a heat interchanger is incorporated in the general heater system. To keep the engine-room air sweet, in some cases a washed supply of air is arranged. Progress has been made in integrating the machine outputs of a station by means of delicate thermo-couples, and this, by means of some of the spare cores of the pilot protection cables, has been extended to more than one generating station of an interconnected system.

Clever devices of the fire-alarm pattern have been installed at static substations, by which can be ascertained from a tape machine what switches have tripped when a disturbance occurs. It is suggested that an extension of this system, coupled with high-frequency, multi-frequency supplies, may yet result in all important switches being operable from the control room. Precision watt-hour meters of a high degree of accuracy are now gradually becoming available. There is a growing practice of installing special condensate mains, and permanent weigh tanks, so that with the aid of these and precision meters accurate routine tests are possible.

It is a growing practice to insert in parallel with the oil circulation system of a prime mover a centrifugal type of oil purifier, by means of which a portion of the oil is for long periods being continuously freed from water and sludge. The machine has, however, to be shut down occasionally for removal of solid matter.

An important device by Piggott has been tried out on a large machine in the States. Atmospheric relief valves in large sizes are undesirable. This device provides a mercury column, which on loss of vacuum in the condenser is arranged through a relay to trip out the main emergency valve, thereby shutting down the set.

The mercury turbine of Emmot, i.e. a "binary fluid cycle," has attracted great interest, but further developments are awaited.

The use of brown coal with over 50 per cent moisture without previous separate drying, is gradually growing. Klingenberg's book on the Golpa station is of considerable interest.

Present attention is, however, rather focused on the Morwell station where gradually the problem is being solved on mechanical stokers with variations of "Welsh setting" for the brickwork. To get full output, however, some simultaneous preheating on a separate grate, by radiation and/or hot air, seems the natural line of progress.

Water-Power Stations.

It is not proposed to examine this question, and very good information will be found in the papers read before the World Power Conference. From these it will be realized that the reaction principle, i.e. the Francis turbine, is being applied to greater heads, and similar progress has been rapidly made corresponding to that on the steam side in going from 750 to 1 500 and now to 3 000 r.p.m. There is a similar cheapening due to more economic utilization of material.

Again, on the exhaust end, due to rational designs of exhaust chambers, leaving losses are being much reduced.

Considerable progress is also being made on high-speed propeller-type runners for low falls. It is very interesting to read of the electrical heating devices which, by slightly raising the temperature of the metal parts, prevent frazil ice from adhering to screen bars and casing and running parts of water turbines in cold climates.

Double operation governing has reached a high degree of efficiency. Brakes are being used to bring large high-speed units to rest as soon as desired after disconnection from the bars.

There is a considerable advance in the efficiency of turbines for small isolated schemes, whilst large turbines are approaching a value of 90 per cent efficiency at the coupling.

Oil-Engine Stations.

In spite of the fact that Great Britain is a coal-producing country, at the present time the total plant capacity of stations using heavy oil in this country is now 50 000 kW. Whilst most of the sets are of small capacity, there is a 750-kW Fullagar engine of English make running, and a Continental maker has supplied a 2 500-kW six-cylinder set to a Belfast firm. Great progress is being made both in the Diesel type (with air injection) and the solid injection type. One British firm is now offering a solid injection two-stroke engine which has been well tried out in the States. Another has recently constructed a number of 1 000-h.p. engines running at 300 r.p.m. Considering the progress made generally in all countries it would seem that the oil engine is passing through a phase corresponding to the development of the high-speed steam engine from the low-speed steam engine.

This will undoubtedly result in a considerable cheapening in price, and a wide use abroad for countries where the oil supply is reliable and at a competitive price. It will also speed up the movement to make a ship's power plant into a power station. It will also result in the increasing use of such engines as stand-by to water-power plants, and one such engine for starting up auxiliaries and essential services may find its place in capital stations as an insurance in the event of total shut-down.

STANDARDIZATION.*

By P. Good, Member.

Historical.

Industrial standardization in the electrical field in Great Britain carried out on a national basis may be said to have started with the proposals made by the late Sir William Preece, acting for the Council of the Institution about the end of the year 1901,† which resulted in the association of the Institution with the four other leading Engineering Institutions in the work of engineering standardization, and the appointment by the British Engineering Standards Association (then called the Engineering Standards Committee) of a Sub-Committee for Standardization of Electrical Plant.

At the meeting called to inaugurate this work, the then Chairman of the Main Committee of the Engineering Standards Committee, Mr. Mansergh, drew attention to the fact that standardization of electrical machinery was already receiving attention in America and Germany. He urged the necessity, not only of national but of international agreement, and it is interesting to note, in passing, that one of the first representatives nominated by the Institution to the Main Committee of the Engineering Standards Committee was Colonel R. E. Crompton, C.B., who founded the International Electrotechnical Commission in 1906, the Institution fathering for many years the British National Committee appointed to co-operate in this work. (The Sectional Electrical Committee of the B.E.S.A. is now the British National Committee of the I.E.C.)

In enumerating matters needing attention, Mr. Mansergh stated that considerable confusion prevailed as to how to define the rated output of an electric motor, also emphasizing the desirability of establishing, in addition to certain physical and mechanical details, the interchangeability of parts. Another important result to be achieved by standardization, as stated by Mr. Mansergh at that meeting, was to discourage the use of varying specifications by individual bodies and persons when one standard specification would serve the purpose. To achieve such a result, however, it was imperative that it should be given an official character, and this, he pointed out, the Engineering Standards Committee would do.

The work thus inaugurated went forward steadily and by the end of 1902, or early in 1903, Committees were hard at work considering the standardization of telegraph and telephone material and electrical machinery.

The necessity for a central organization to carry out standardization over the whole range of the engineering industry, thus early recognized, has not grown less, so

* A review of progress (see p. 150). Reprints, in pamphlet form, price 2s. 6d. each, can be obtained from the Secretary of the Institution.

† It is not suggested that this was the commencement of electrical standardization. The first edition of the I.E.E. Wiring Rules was issued in 1882. The standardization of electric cables was commenced by the Cable Makers' Association in 1899, and other instances could no doubt be cited.

that, at the present time, in all matters of electrical standardization, the Institution co-operates actively and gives very substantial financial support to the work of the B.E.S.A.

Development.

That electrical engineers quickly realized the far-reaching importance of co-operative standardization is well indicated by the large number of those now voluntarily taking part in the work. The British Engineering Standards Association (B.E.S.A.) has at the present time 70 Committees preparing electrical specifications, whilst the Electrical Research Association (E.R.A.) has a large number of Committees either preparing standard methods of test or carrying out researches which will in due course provide data to form the basis of standard specifications.

The Institution, through its Wiring Rules Committee, its Ship Electrical Equipment Committee and its Committee on Rules and Regulations for Electricity Supply, is itself directly engaged in important co-operative standardization.

Committees considering questions of electrical standardization (mostly for reference to the B.E.S.A.) exist in the following organizations :—

British Electrical and Allied Manufacturers' Association,
Cable Makers' Association,
Electric Lamp Manufacturers' Association,
Incorporated Municipal Electrical Association, and
Municipal Tramways Association ;

whilst practically every industrial and scientific body in the electrical industry lends its active support to the work.

In 1919, a Government Interdepartmental Committee was set up to co-ordinate the electrical requirements of the Government Departments, and this Committee works in close co-operation with the B.E.S.A., with the intention that, as far as possible, Government requirements shall be in accordance with general industrial practice. This Committee adopts, as far as possible, existing British Standard Specifications, but where Government requirements are special, the Interdepartmental Committee has prepared a number of specifications covering somewhat more detail than is considered appropriate for ordinary industrial Standard Specifications, and these Government Department specifications are published by the Stationery Office. This step, initiated in connection with electrical requirements, has resulted in a widespread application among Government Departments of the principle of standardization, so that there are now Interdepartmental Committees preparing specifications for a wide range of general stores.

An important development during 1925 has been the widening of the basis of membership of the B.E.S.A. whereby those associating themselves with the work will be kept in close touch with its progress and with standardization and simplification in other parts of the world. Members of the Committees of the B.E.S.A. will in future be known as Honorary Members, and ordinary membership will be available to all connected with the industry on payment of a small annual fee. In return for this, members will be in a position to secure direct representation of their interests on the Main Executive Committee through a duly elected Advisory Council, certain free copies of specifications and free advice on all matters of standardization, whilst they will have the additional satisfaction of knowing that they are assisting in a work of national importance.

Scope.

Whilst it is probable that, at this date, no better terms than "standardization" and "simplification" can be found to describe the scope of the work thus undertaken, this scope is not yet well understood, as the expression "standardization" has, to a great many people, only a limited meaning.

The B.E.S.A., in carrying out the task laid upon it, has endeavoured to set up standards of quality in order to limit the use of unnecessary and unsuitable materials and sizes, as well as to bring about a greater degree of equity in the purchase and sale of materials and electrical apparatus generally, not the least valuable result of the work being that the general use of agreed specifications has made a comparison of tenders more satisfactory. Because of this, the term "standardization" has grown to mean, in the minds of engineers, not only a simplification in the number of types and sizes and the securing of interchangeability, but also the laying down of performance rules or codes for all types of apparatus, including measuring instruments, prime movers, generators, transformers and motors. Thus broadly the term "standard," in addition to being a measure of quality or standard of comparison, means a common unified practice, method or dimension, which it is to the interest of industry and the community to adopt.

Useful standardization and simplification are not, however, confined to technical requirements, but are equally of value on the commercial side. An outstanding illustration of this form of standardization is to be seen in the I.E.E. Model Conditions of Contract. There are also a number of other standardized conditions of contract in operation, and whilst in most cases these have been agreed between definite groups of purchasers and makers, it is probable that they would be still more effective if carried out under an organization bringing into the deliberations interests other than those directly concerned in the making of the contract.

Conditions of employment have also been standardized to a certain extent in the electrical industry.

Progress in Great Britain.

Probably one of the most valuable pieces of work brought to completion during the past year is the British Standard Glossary of Terms used in Electrical Engineering. This Glossary, intended to cover the technical terms ordinarily used in electrical science and in its application to the electrical industry, comprises some 2 000 terms and will have the important effect of stabilizing the language of the industry. These terms and definitions have been prepared with the assistance of a large number of experts, and the Editing Committee, consisting of Mr. C. C. Wharton and Lt.-Col. K. Edgcumbe, has given untiring service for more than 3 years to co-ordinating and unifying the mass of material thus collected.

This Glossary has been adopted by the International Electrotechnical Commission as the basis for an International Glossary now in preparation, and completes the first stage of the work started by the Institution in 1908.

In the table on pages 498 and 499 an attempt has been made to illustrate the range of the work coming under the general term "standardization" as carried out by the electrical industry in this country (excluding that being done by individual firms), by sub-dividing the subject into a number of headings as follows :—

Nomenclature and Symbols.
Simplification of Types and Sizes.
Standardization of Tests.
Interchangeability of Parts.
Rules for Performance (Rating, etc.).
Quality of Material.
Conditions of Contract and Sale, and Schedules of Guarantee and Performance.

The table is believed to be complete in so far as technical standardization of electrical material is concerned, but it may not be so complete in regard to the conditions of contract. Standardized conditions of employment have not been shown, but could probably with advantage be included in future reports.

An examination of this table will show that a very substantial measure of progress has been made. Moreover, it has been found that, in the opinion of the industry, the specifications and other documents are of great value not only to the manufacturer and user but to the community in general. It is recognized that generally acceptable technical specifications and standard conditions of contract form very efficient machine tools for the rapid completion of a commercial transaction, saving an immense amount of detailed work and leaving the consulting engineer free to devote his attention to the broad questions which an engineering problem as a whole presents. Also the work of preparing these standards involves the pooling of a vast amount of technical knowledge, so that the Committee work of the B.E.S.A. and the E.R.A. is probably one of the finest continuation courses obtainable for senior engineers.

Future Work in Great Britain.

The growing recognition of the necessity for a standard of comparison for complex articles as well as the necessity for simplifying practice by the elimination of unnecessary sizes, is likely to be reflected in the production of an increasing number of new specifications in the near future.

The increase in the output and the rapid spread of the distribution of electric power on a large scale have created quite new problems, and the question of the rating of switchgear generally is one to which much attention is being given at the present time. The necessity for Standard Specifications for materials for overhead line construction, radio apparatus, insulating materials and tramway and railway equipment, is recognized and early progress in this direction is likely.

It is becoming clear that industrial motors of small and medium sizes are, like the electric lamp, being looked upon as ordinary articles of commerce, and attention is being directed to the possibility in the near future of having the speeds and some of the leading dimensions unified. The Government Interdepartmental Committee has already included recommendations on this question in its specifications for motors.

The following are a few of the specifications which the B.E.S.A. is likely to issue early in 1926 :—

Electrical Performance of Transformers, Rotary Converters and Fractional Horse-Power Motors

(being the remaining sections of the revision of the old Standardization Rules).

Tests for Flame-proof Enclosures for Electrical Apparatus.

Standardization in the British Dominions.

Fairly complete machinery now exists whereby the closest co-operation has been achieved between those preparing electrical specifications in this country and engineers in all branches of the British Empire. In Canada and Australia the Local Committees of the B.E.S.A. have formed independent Standardization Associations, and the Australian Association has obtained permission to reproduce the British Standard Specifications as Australian Standards when applicable to local conditions. The B.E.A.M.A. Overseas Committees also co-operate in the work.

Standardization in other Countries.

The recognition of the urgent necessity for national Standard Specifications is now practically universal, and the preparation of such specifications and the laying down of standard rules are being proceeded with in practically all countries. Generally speaking, the organization of the work follows closely that adopted in this country. A large amount of work has already been done in Germany and the United States.

International Electrotechnical Commission.

With the increasing industrial interdependence of the different countries of the world, the same necessity for an equitable basis of tender for exports and imports of electrical merchandise has led, as briefly referred to above, to the formation of the International Electrotechnical Commission. Thus the tendency is growing to have the standards in all countries developing, in so far as fundamentals are concerned, along certain agreed lines, based on international discussion and goodwill, and much valuable interchange of knowledge has thereby been promoted. Progress in this work has been marked. In addition to the international symbols and an agreed international standard for the resistance of commercial annealed copper, agreement has practically been reached for an international standard for the resistance of aluminium. International agreement has also been reached in regard to temperature-rises for electrical machines, and international ratings for prime movers, both steam and hydraulic, are in preparation.

STANDARDIZATION OF ELECTRICAL PLANT, APPARATUS

Where the document referred to in the table is a British Standard Publication issued by the B.E.S.A. a reference number only is given. In all other cases the organization responsible for the document referred to is indicated by the abbreviation given in brackets as follows :—

Institution of Electrical Engineers (I.E.E.) ; International Electrotechnical Commission (I.E.C.) ; Electrical Research Association (E.R.A.) ; Interdepartmental Government Committee (G.D.S.) ; British Electrical and Allied Manufacturers Association (B.E.A.M.A.) ; Municipal Tramways Association (M.T.A.) ; Incorporated Municipal Electrical Association (I.M.E.A.).

	NOMENCLATURE AND SYMBOLS	SIMPLIFICATION OF TYPES AND SIZES	STANDARDIZATION OF TESTS (*a*)
GENERAL	GLOSSARY OF ELECTRICAL TERMS (205) *Elemental Terms* *Fundamental Terms :—* *Electrostatic* *Magnetic* *Derived Terms* *Units* *Technological Terms* FIRE-RESISTING PROPERTIES OF INSULATING MATERIALS (E.R.A. Ref. L/81) LETTER SYMBOLS (I.E.C. 27) GRAPHICAL SYMBOLS (108) GRAPHICAL SYMBOLS (I.E.C. 35*)	VOLTAGES FOR NEW SYSTEMS (77) COPPER WIRES, ANNEALED (128) COPPER WIRES, ENAMELLED (156)	SPARK GAPS FOR MEASUREMENT OF VOLTAGES (E.R.A. Ref. L/S2) FIRE-RESISTING TESTS, CLASSIFICATION OF (E.R.A. Ref. L/S1) FIBROUS MATERIALS (E.R.A. Ref. A/S1) ELECTRIC STRENGTH OF FIBROUS MATERIALS (E.R.A. Ref. A/S2) PRESSBOARD (E.R.A. Ref. A/S3) PRESSBOARD (231) VULCANIZED FIBRE (E.R.A. Ref. A/S4) VULCANIZED FIBRE (216) INSULATING PAPER (E.R.A. Ref. A/S5) VARNISHED FABRIC AND PAPER BOARDS AND TUBES (E.R.A. Ref. A/S6) INSULATING VARNISHES, PAINTS AND ENAMEL PAINTS (E.R.A. Ref. A/S9) NON-IGNITABLE BOARDS AND MOULDINGS E.R.A. Ref. A/S10) TEXTILE FABRICS, UNVARNISHED (E.R.A. Ref. A/S11) HARD COMPOSITE DIELECTRIC MATERIAL (E.R.A. Ref. B/S1) LUBRICATING OILS (210) FUELS FOR HEAVY OIL ENGINES (209) SYNTHETIC RESINS (238)
PRIME MOVERS	HYDRAULIC TURBINES (I.E.C. 29)	Reciprocating Steam Engines (42)	
MACHINES AND TRANSFORMERS	SECTION 2 OF GLOSSARY (205) *Generators* *Motors* *Composite Machines* *Transformers* *Parts of Machines* *Parts and Types of Windings* Terminal Markings for Transformers (171)	CARBON BRUSHES (96)	Insulating Oils for Transformers (148)
SWITCHGEAR AND CONTROL GEAR	SECTION 3 OF GLOSSARY (205) *Circuit Opening and Closing Devices* *Starters* *Controllers* *Regulators* *Switchgear and Control Gear* MARKINGS FOR SWITCHBOARD BUSBARS AND CONNECTIONS (158) Terminal Markings for Motor Starters and Controllers (117 and 118)	SWITCHGEAR EQUIPMENT, D.C. (194*) MOULDED INSULATING BUSHES (157) WATERTIGHT GLANDS (94) CABLE SOCKETS (91)	Insulating Oil for Switches (148)
METERS AND MEASUREMENT	SECTION 4 OF GLOSSARY (205) *General* *Indicating and Recording Meters* *Integrating Meters* MARKINGS FOR INSTRUMENT TERMINALS (89) Terminal Markings for Instrument Transformers (81)	MAGNET STEEL ROLLED SECTIONS (107)	(*a*) Nearly all the documents reviewed include tests. Those given in this column define with some precision the method of test with the object of standardizing the test.

AND MATERIAL IN GREAT BRITAIN (1925).

The main reference to these documents is given in capitals under the heading which particularly applies. Cross references under other headings are given in small type.

NOTE.—In addition to the specifications for electrical material and apparatus there are a large number of B.E.S.A. specifications for iron, steel, copper and aluminium and their alloys, and other materials, as well as specifications for pipes, rolled steel joints, keys and keyways, limits and fits, fire extinguishers, etc., which are of use to electrical engineers but are not included in this report.

INTERCHANGEABILITY OF PARTS	RULES FOR PERFORMANCE	QUALITY OF MATERIAL	CONDITIONS OF CONTRACT AND SALE, AND GUARANTEES OF PERFORMANCE
SCREW THREADS, B.S.W. (7270) SCREW THREADS, B.S.F. (84) SCREW THREADS, B.A. (93) Conduit Fittings (31) HEADS FOR B.A. SCREWS (57)		STANDARD RESISTANCE OF ANNEALED COPPER (I.E.C. 28) ELECTROLYTIC COPPER WIRE BARS, CAKES AND BILLETS (198) SOFT SOLDERS (219) METALLIC RESISTANCE MATERIALS (115) VULCANIZED FIBRE (216) SYNTHETIC RESINS (238) PRESSBOARD (231)	MODEL GENERAL CONDITIONS OF CONTRACT (I.E.E.) CONDITIONS OF SALE: GOODS ON SALE OR RETURN (B.E.A.M.A.)
	RECIPROCATING STEAM ENGINES (42) STEAM TURBINES (132) GAS ENGINES (120) HEAVY OIL ENGINES:— DIESEL (211) SURFACE IGNITION TYPE (212) COLD STARTING (213)	FUELS FOR HEAVY-OIL ENGINES (209)	
	INDUSTRIAL MOTORS AND GENERATORS (168) LARGE GENERATORS AND MOTORS (169 and 226) TRACTION MOTORS (173) FRACTIONAL H.P. MOTORS (170) TURBO-ALTERNATORS (225) D.C. MOTORS (G.D.S. 2) INTERNATIONAL RATING FOR ELECTRICAL MACHINES UP TO 750 kVA (I.E.C. 34)	INSULATING OILS FOR TRANSFORMERS (148) Motors (G.D.S. 2)	CONDITIONS OF SALE:— SLOW SPEED ENGINES (B.E.A.M.A.) GAS AND OIL ENGINES (B.E.A.M.A.) WATER COOLING APPARATUS (B.E.A.M.A.) GUARANTEES:— TURBINES (H.P.) AND TURBO-ALTERNATORS (B.E.A.M.A.–I.M.E.A.) CONDENSING PLANT (SURFACE) (B.E.A.M.A.–I.M.E.A.) COOLING WATER APPARATUS:— NATURAL DRAUGHT COOLING TOWERS (B.E.A.M.A.–I.M.E.A.) ROTARY CONVERTERS AND TRANSFORMERS, AND MOTOR CONVERTERS (B.E.A.M.A.–I.M.E.A.)
BATTERY VEHICLE PLUG AND SOCKET (74) Switch-fuses (G.D.S. 6) Cut-outs (G.D.S. 7) CUT-OUTS (88)	MOTOR STARTERS (82, 117, 140, 141, 147, 155 and 167) MOTOR CONTROLLERS (118, 123 and 129) SWITCHES AND CIRCUIT BREAKERS (109, 110, 116, 124, 126, 127 and 130)	Charging Plug and Socket (74) SLATE SLABS (160) BUSBARS AND CONNECTIONS (159) Cut-outs (G.D.S. 7) Switch with Fuses (G.D.S. 6) Insulating Oil for Switches (148)	
	ELECTRICITY METERS (37) INSTRUMENT TRANSFORMERS (81) INDICATING INSTRUMENTS (89) RECORDING INSTRUMENTS (90) INDICATING INSTRUMENTS (G.D.S. 3)	ENAMELLED PLAIN COPPER WIRE FOR ELECTRICAL INSTRUMENTS (156)	CONDITIONS OF SALE:— ELECTRICITY METERS (B.E.A.M.A.)

Continued on pages 500 and 501.

STANDARDIZATION OF ELECTRICAL PLANT, APPARATUS

	NOMENCLATURE AND SYMBOLS	SIMPLIFICATION OF TYPES AND SIZES	STANDARDIZATION OF TESTS (a)
TRANSMISSION AND DISTRIBUTION	Section 5 of Glossary (205) *Systems* *Mains and Feeders* *Conductors and Cables* *Constructional Features and Miscellaneous*	Hard-drawn Copper Wires and Cables (125) Insulated Cables, Annealed Copper (Rubber, Paper and Jute and Bitumen Insulated, Tough Rubber Compound, Lead-covered and Bitumen-covered, Braided and Armoured and Flexibles) (7) Porcelain Insulators (137) Hard-drawn Aluminium Conductors (215)	Porcelain Insulators (137)
ELECTRO-CHEMISTRY	Section 6 of Glossary (205) *Primary Cells* *Accumulators* *Electro-metallurgy*		
TRACTION	Section 7 of Glossary (205) *Track and Overhead Construction* *Vehicle Equipment* *Miscellaneous* Steel Conductor Rails, Method of Stating Resistance of (68)	Tramway Poles (8) Tramway rails and Fishplates (2) Tramway Wheel Centres (149) Trolley Wire (M.T.A. 2) Overhead Wire Fittings (M.T.A. 4) Steel Span and Guard Wires (M.T.A. 3) Galvanized Steel Wire for Signalling Purposes (163)	Steel Conductor Rails—Temperature Coefficient for (68)
LIGHTING, HEATING, AND DOMESTIC APPLIANCES	Section 8 of Glossary (205) *Illumination and Photometry* *Filament Lamps* *Arc and other Lamps* *Heating and Cooking* *Fittings and Accessories* *Domestic* Illumination terms from this section issued separately (233)	Resistance Wires and Materials (117) Conduit Fittings (31) Wall Plugs (73) Ceiling Roses (63) Watertight Fittings (97)	Rubber Cables (G.D.S. 1, 5, 9 and 10) Dry Cells (Telephone) (G.D.S. 4) Dry Cells (Torch) (G.D.S. 11)
TELEGRAPHS AND TELEPHONES	Section 9 of Glossary (205) *Offices* *Exchanges* *Stations* *Systems* *Circuits* *Calling Devices* *Transmitters* *Receivers* *Relays and Repeaters* *Switching Devices* *Lines and Line Equipment* This section also issued separately (204)	Line Wire Material:— Hard-drawn Copper Wire (174) Bronze Wire (175) Copper Binding and Jointing Wire (176) Copper Tapes and Binders (177) Bronze Tapes and Binders (178) Copper Jointing Sleeves (179–180) Bronze Jointing Sleeves (181) Galvanized Line Wire (182) Galvanized Stay Wire (183) Galvanized Binding and Jointing Wire (184) Red Fir Wood Poles (139) Steel Poles (134*) Tough Rubber-covered Cables (G.D.S. 5) Rolled Magnet Steel Section for Bell Receiver (107)	
RADIO-COMMUNICATION	Section 10 of Glossary (205) *Ether and Ether Waves* *Aerials and Aerial Construction* *Transmission and Reception* *Valves and their Properties* *Circuits* *Amplifiers and Relays* This section also issued separately (166)	Ebonite Panels (234)	Ebonite Panels (234)
MISCELLANEOUS	Section 11 of Glossary (205) *X-Ray, Electro-medical, Electric Lifts*	Insulated Cables for Automobiles (5002) Low-tension Flexible Electric Cords and Cables (Aircraft) (4 E. 3) High-tension Electric Ignition Cables (Aircraft) (3 E. 1) Low-tension Electric Cables (Aircraft) (E. 11) Magnet Steel Sections (107)	(a) Nearly all the documents reviewed include tests. Those given in this column define with some precision the method of test with the object of standardizing the test.

AND MATERIAL IN GREAT BRITAIN (1925)—*continued.*

INTERCHANGEABILITY OF PARTS	RULES FOR PERFORMANCE	QUALITY OF MATERIAL	CONDITIONS OF CONTRACT AND SALE, AND GUARANTEES OF PERFORMANCE
		PORCELAIN INSULATORS (137) TOUGH RUBBER-COVERED CABLES (G.D.S. 9)	
Dry Cells for Telephone and Similar Purposes (G.D.S. 4) Dry Cells for Torches, etc. (G.D.S. 11)			CONDITIONS OF SALE:— X-RAY AND ELECTRO-MEDICAL (B.E.A.M.A.)
TRAMWAY WHEEL CENTRES (149-150)	LAMPS (161) *Traction Vacuum* *Train-lighting Vacuum* *Train-lighting Gasfilled*	TRAMWAY TYRES (101) TRAMWAY AXLES (102) Tramway Wheel Centres:— Wrought Iron (149) Cast Steel (150) TRAMWAY POLES (8) Tramway Rails and Fishplates (2) TROLLEY WIRES (M.T.A. 2) STEEL WIRE SPANS AND GUARDS (M.T.A. 3) Overhead Wire Fittings (M.T.A. 4) CREOSOTE FOR TIMBER (144)	
CONDUIT FITTINGS (31) CEILING ROSES (67) TWO-PIN WALL PLUGS (73) GOLIATH LAMPHOLDERS (98)	WIRING REGULATIONS (I.E.E.) LAMPS (*Vacuum, Gasfilled*) (161)	RUBBER CABLES FOR ELECTRIC LIGHT AND POWER (G.D.S. 1) TOUGH RUBBER TELEGRAPH AND TELEPHONE CABLES (G.D.S. 5) DRY CELLS (TELEPHONE) (G.D.S. 4) DRY CELLS (TORCH) (G.D.S. 11) Two-pin Wall Plugs (73)	
		Red Fir Wood Poles (139) Line Wire Material:— Hard-drawn Copper Wire (174) Bronze Wire (175) Copper Binding and Jointing Wire (176) Copper Tapes and Binders (177) Bronze Tapes and Binders (178) Copper Jointing Sleeves (179–180) Bronze Jointing Sleeves (181) Galvanized Line Wire (182) Galvanized Stay Wire (183) Galvanized Binding and Jointing Wire (184)	
		EBONITE PANELS (234)	
MAGNETOS FOR INTERNAL COMBUSTION ENGINES (5027)		Cables for Automobiles (5002)	

INSTITUTION NOTES.

Jubilee of the Telephone.

The Council are making arrangements for the celebration of the fiftieth anniversary of the first public use of the telephone (25th June, 1876). Particulars will be announced in due course.

Lending Library.

A new edition of the Lending Library Catalogue has been published. Copies can be obtained on application to the Secretary.

Associate Membership Examination Results.

OCTOBER 1925, SUPPLEMENTARY LIST.*

Passed.

Aschmann, G. D. (New Zealand).
Irvine, H. B. (New Zealand).
Mackersey, C. A. (New Zealand).
Paine, G. R. (Australia).

Passed Part II only.

Swift, L. A. (New Zealand).

The Late Mrs. Hertha Ayrton.

A biography of the late Mrs. Ayrton, by Evelyn Sharp, has recently been published. Mrs. Ayrton was a Member of the Institution from 1899 until her death in 1923, and was the widow of the late Professor W. E. Ayrton, F.R.S., who held the office of President in 1892.

Gas and Electricity Undertakings.

With the concurrence of the Council of the Institution and of the National Gas Council, a Joint Committee has been set up with the following reference: "To consider whether in the national interest an inquiry might advantageously be held into the possibility of closer co-operation between gas and electricity undertakings in promoting capital and fuel economy in the supply to the public of energy derived from coal," with the understanding that no Reports or Discussions of the Committee are to be published without the consent of both Councils.

The Committee is constituted as follows :—

Mr. R. A. Chattock Mr. J. S. Highfield Mr. G. W. Partridge Mr. C. P. Sparks, C.B.E. Mr. W. B. Woodhouse	Nominated by the Council I.E.E.
Mr. D. Milne Watson, D.L. Mr. W. Cash, F.C.A. Sir A. Duckham, K.C.B. Mr. A. W. Smith Mr. C. Wood, O.B.E., F.C.S.	Nominated by the National Gas Council.

The Science Museum, South Kensington.

The Annual Conversazione of the Institution will be held on Thursday, 24th June, at the Science Museum, South Kensington, instead of at the Natural History Museum. In this connection the following particulars of the collections of electrical apparatus now on view at the Science Museum have been supplied by the Director and Secretary of the Museum :—

"The collections at the Science Museum which illustrate the various branches of electrical engineering have now been placed on view in the galleries of the new Museum building in Exhibition-road, where they occupy more than 12 000 sq. ft. Electric power and lighting, as well as telegraphy, telephony and radio-telegraphy, are shown in Gallery XXVI on the first floor, while electrical instruments are arranged in Gallery XLIII on the second floor. Atmospheric electricity and lightning protection are included with the geophysical collection in Gallery XLIV.

"Advantage has been taken of the additional space now available to show many objects of great historical and technical interest which had previously been in store. The collection of historical objects which was lent by the Institution of Electrical Engineers to the National Collection in 1923 is now prominently exhibited in all these galleries, and of it Clarke's magneto-electric machine, an early Gramme alternator, an early Edison 10-kW two-pole dynamo, a Gramme dynamo from the Crystal Palace 1882, Ladd twin-armature dynamos, a coil of the 10 000-volt 1 000-kW Ferranti dynamo of 1889, a 10 000-volt Ferranti cable and fuse, and a 10 000/2 500-volt Ferranti transformer of 1890 are shown in Gallery XXVI.

"An extensive collection of historical switches and lampholders, many of which were presented to the Institution by Mr. Killingworth Hedges, and a collection of 86 early incandescent lamps are exhibited with the electric lighting collection.

"A valuable collection of early meters includes an Edison electrolytic meter, recording meters by Richard Frères, Kelvin and Walker and Laurence Scott, also Scheeffer and Forbes meters.

"Among the early arc lamps are the Holmes arc lamps from the South Foreland.

"The collections also include an original Pacinotti dynamo and the original dynamos of Ladd, Wheatstone, Wilde, Varley and Siemens; also original Gaulard and Gibbs transformers. In addition, there is a very extensive collection of electrical measuring instruments of much historical interest.

"In that part of the collection which illustrates electric lighting, Swan's carbon pencil lamp of 1879 and specimens of early Swan carbon and cellulose filaments, also the Edison bamboo filament lamp of 1879 are important.

"The collection illustrating electrical communication is now in the same gallery and includes an early siphon recorder (one of the first six made for the Eastern Telegraph Co.), a number of coils, condensers, etc., used by Marconi and his assistants in the early days of wireless telegraphy, an early manual telephone exchange, an early Strowger automatic telephone instrument (the system is still used, though greatly changed), the original Reis telephone and Sir William Cooke's original alarum,

* See pages 92 and 192.

as well as a large number of obsolete telephone receivers and transmitters and many submarine cable specimens, all of which form part of the Institution's collection.

"Other objects of historical importance which are on exhibition are:—In telegraphy, Sir Francis Ronalds's electrostatic telegraph; Cooke and Wheatstone's instruments; Hughes, Edison, Murray and Creed type-printing; Atlantic cable specimens and submarine cable apparatus. In telephony, early Bell telephones and original Hughes microphones. In radio-telegraphy, historical exhibits relating to the early work of Prof. D. E. Hughes, Sir Oliver Lodge, Senatore Marconi and others. The collection of thermionic valves includes the original Fleming diodes, together with many modern examples. Some broadcasting microphones are shown, and there are scale models of the aerial equipment of the new Government station at Rugby. There is also an important working model of the automatic telephone systems for London and the provinces, the former as described in a recent Institution paper. The model was exhibited in the Government Building at Wembley and has been installed by the Post Office. This will be demonstrated daily from the 1st April.

"On the second floor the collection of electrical instruments is in course of arrangement. It includes several which have been lent by the Institution, e.g. a Byrne cell made by Ladd, Kelvin's ampere balance No. 1, Baily's apparatus to show Arago's motion, and a series of early vacuum and X-ray tubes made by Sir William Crookes and Mr. A. A. Campbell Swinton.

"In the section illustrating Lightning Protection are a number of objects contributed by Mr. Killingworth Hedges."

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 February–25 March, 1926:—

	£	s.	d.
Adams, C. (London)		5	0
Ambrose, G. S. (Rugby)		3	6
Anonymous		8	6
Baguley, E. (London)		10	0
Baldwin, F. G. C. (Wylam-on-Tyne)		5	0
Bamford, P. E. (Birmingham)		10	0
Barnard, A. S. (Manchester)	1	5	0
Barr, M. (New York)	1	1	0
Barrand, P. C. (Loughborough)		5	0
Barton, T. (Wigan)		5	0
Baty, J. E. (London)		15	0
Beak, A. L. (London)		5	0
Beard, A. T. J. (London)		3	6
Ballamy, L. C. F. (Hong-Kong)	1	0	0
Benton, L. C. (Manchester		5	0
Birkby, H. (Blackheath)		10	0
Bland, J. G. (Brighton)		2	0
Bloome, J. (London)		8	6
Bolton, E. S. (Leeds)		5	0
Bose, L. C. (Srinagar, India)		5	0
Braid, D. H. (Edinburgh)		3	6
Brent, W. H. (Rayleigh)		6	0
Brookes, A. (Beeston)		5	0*

* Annual Subscription.

	£	s.	d.
Brown, E. (Blackburn)		10	6
Browne, B. F. (Santos, Brazil)	1	10	0*
Bruce, R. (Leeds)		3	6
"Buggins" (Egypt)		10	0
Bullen, A. T. (Bedford)		5	0
Burge, H. (Chelmsford)		10	0
Burgess, P. J. (Birmingham)		5	0
Burt, B. M. (Manchester)		8	0
Butcher, P. H. C. (Sutton Coldfield)		5	0*
Butler, C. F. (Glasgow)		10	0
Buttenshaw, H. F. (Sydney)		10	0*
Campbell, A. C. (Woodford Green)		2	6
Campion, R. H. (Torquay)	1	1	0*
Carr, L. S. (Birmingham)		10	0*
Cash, H. J. (London)		10	0
Casson, W. (London)		2	6
Castello-Sosa, A. (Mexico)		5	0
Charlton, H. C. (Newcastle-on-Tyne)		2	6
Chatterjee, S. K. (Khandwa, India)		5	0
Claret, W. E. (Wakefield)		5	0*
Cleaver, R. L. (London)		13	0
Clegg, G. D. (Birmingham)		5	0*
Clements, V. A. H. (London)		2	6
Clough, N. (London)		15	0
Coates, A. W. (Macclesfield)		5	0
Corbin, C. (Peru)		5	0
Corke, L. C. W. (Stockport)		5	0
Coventon, G. L. (Chepstow)		5	0
Cowie, J. R. (London)	1	1	0
Cox, P. H. (Cheltenham)		5	0
Crisp, M. H. T. (Namtu, Burma)	1	5	0
Dahl, G. (Vasteras, Sweden)		3	6
Dalton, W. T. (Newcastle-on-Tyne)		10	6
Darling, W. N. (Airdrie, N.B.)		5	0
Davids, W. da F. B (Brazil)		15	0
Debley, W. J. F (Cardiff)		5	0
Dennis, T. H. (Singapore)		9	0
Dinham-Peren, A. E. H. (London)		5	0
Donaldson, T. (Glasgow)		3	6
Dootson, J. (Troon, N.B.)		3	6
Downie, C. E. (Paisley)		5	0
Dransfield, T. E. (Manchester)		5	0
Driscoll, L. F. A. (Newport, Mon.)		3	6
Dupree, F. H. (Singapore)		5	0*
Electro-Harmonic Society		18	10
Embrey, T. J. (Smethwick)		3	6
Emerson, S. J. (Runcorn)		3	6
England, P. C. (London)		3	6
Flanagan, J. (Middlesbrough)		5	0
Forrest, F. (Birmingham)		10	6*
Foulds, W. (Blackpool)		5	0
Francis, M. R. (Swansea)		5	0
Gallon, W. A. (Billingham-on-Tees)		3	6
Galloway, J. (Calcutta)		4	0
Gangoly, U. (Khandwa, India)		1	0
Geary, F. A. (London)		5	0
Gibbard, H. E. (Banbury)		5	0*
Glenny, A. P. (Belfort, France)		13	6
Goode, R. W. (Coventry)		6	0
Gould, F. (Sunderland)		5	0*
Grant, L. C. P. M. (Calcutta)		10	6

* Annual Subscriptions.

	£	s.	d.
Green, J. D. (Leeds)		10	0
Greening, A. C. (London)		5	0
Guest, H. (London)		5	0
Hacking, J. P. (Pittsburgh, U.S.A.)		5	0
Hailey, G. (Hong-Kong)		8	6
Hall, J. C. (Croxley Green)		5	0
Hands, H. F. (Birmingham)		8	6
Haworth, P. S. (Darwen)		5	0
Helden, A. E. (North Shields)		5	0
Henderson, J. (Belvedere)		5	0
Higson, W. (Valparaiso)	1	5	0
Hitch, A. T. (Bombay)		5	0
Hodgson, A. J. (London)		10	6
Hollin, A. S. (Bradford)		5	0*
Hood, T. (Bristol)	1	1	0
Howarth, T. (Manchester)		2	6
Howell, A. (Gosforth)		5	0
Howell, A. (West Bromwich)		5	0
Hugh-Jones, T. W. (Peru)		10	6
Hunter, G. (Gateshead-on-Tyne)		2	6
Jackson, W. G. C. (Woodford Green)		10	0
Johnson, C. W. (London)		3	6
Johnson, H. H. (London)		10	0
Keeley, D. (Maidstone)		10	6
Kerr, H. (Horwich)		5	0
King, A. J. (Manchester)		1	6
King, H. H. (Watford)		5	0
Knight, R. P. (Sheffield)		3	6
Knill, E. P. (Bristol)		5	0*
Lappin, H. (Salford)		5	0
Law, G. C. (London)		5	0
Lee, H. C. (Peru)	1	5	0*
Lingard, J. (Leith, N.B.)		15	0
Lovell, W. D. (Bradford)		5	0
Loveridge, C. W. (Bowdon)		5	0
Lunn, A. L. (Manchester)		10	6*
McGeoch, W. (Birmingham)	1	1	0*
McLean, G. O. (Calcutta)		4	6
McMaster, A. W. (Old Kilpatrick, N.B.)		5	0
MacWhirter, R. (Glasgow)		5	0
Maiden, R. S. (Colne)		5	0
Mallinson, A. B. (Salford)	1	1	0*
Marks, F. E. T. (London)		2	6
Marsh, F. R. (Hong-Kong)	10	10	0
Massey, W. T. (Manchester)		5	0
Mathieson, D. (Singapore)		5	0
Meneze, J. A. (London)		5	6
Mohring, A. E. (Hornchurch)	1	5	0*
Morse, A. H. (New York)		10	0
Newburn, E. A. (Rochdale)		5	0
Newell, C. A. (Blackheath)	1	0	0
Nicholson, C. H. (Hull)		5	0
Orrell, W. (Lostock)		2	6
Oughton, F. C. (West Bridgford)		5	0*
Outram, F. C. (Hull)		3	6
Palmer, E. W. (London)		3	6
Paton, A. M. (West Hartlepool)		5	0
Payn, H. (Boston)		5	0*
Pearson, E. M. (York)		5	0
Phipps, W. A. (Singapore)		8	6

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NOTES ON THE TESTING OF STATIC TRANSFORMERS.

By J. LINDLEY THOMPSON, M.Sc., Member, and H. WALMSLEY.

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SUMMARY.

The paper describes the usual methods adopted in the commercial testing of static transformers. Emphasis is laid on the need for accuracy, and methods are suggested whereby it can be obtained.

The drying-out of transformers, the determination of dryness, and the measurement of insulation resistance are discussed. The measurement of the iron loss and load loss is described, together with methods for obtaining greater accuracy.

The measurement of form factor and its effect on the loss measurements are dealt with; and methods for determining the ohmic resistance, also corrections for the same, are detailed.

The loading of transformers for a full-load test, and the temperature-rise readings obtained on this test, are discussed. Over-potential and pressure testing are described, and the methods of measuring high voltages are detailed.

In this paper the authors describe how transformers can be efficiently tested, and also some of the methods employed for determining and correcting any measurements taken.

Accurate results are essential in all the various tests. This tends to create confidence in the mind of the customer, and also gives the designer and manufacturer confidence in their product.

Testing serves as a check on workmanship, materials, design, and drafting, and should function as the most critical inspection of the product.

Apart from the visual inspection and the testing of mechanical attachments, the following general tests are required on all transformers, in order to ensure their satisfactory design and manufacture :—

(1) Ratio.
(2) Polarity.
(3) Iron loss and magnetizing current.
(4) Copper or load loss, and impedance.
(5) Resistance, cold and hot.
(6) Full-load temperature-run.
(7) Over-potential tests.
(8) Pressure tests.

ACCURATE TESTING.

To ensure accurate testing there are a few simple precautions that should always be taken.

It is essential first of all to study the requirements of the transformers under test as regards the instruments most suitable, in order to prevent overloading or subjecting them to a higher pressure than that for which they are designed. This precaution may seem obvious, but unless carried out it may easily involve the destruction of, or damage to, valuable instruments.

The method of carrying out the test should be studied so that the most accurate one may be employed. The means employed also require thought, so that the best and most favourable condition may be selected. A little thought in this direction may often save the overloading of a generator or auxiliary transformer, and so tends to lengthen the life of the test plant. Where a considerable amount of auxiliary apparatus and plant is required to carry out a particular test, it is wise to draw up a clear, full diagram of connections and also to set out the sequence of the operations to be performed, together with a table of all load currents, voltages, frequencies, oil flow, and water quantities, etc., that will be required. To ensure accurate testing, it is essential that all instruments should be well cared for, checked, and calibrated at regular intervals.

Preliminary tests should be carried out on all transformers during the process of manufacture, in order to ensure a satisfactory product and prevent, as far as possible, time and labour being spent on a defective unit. These tests being repeated in the final stage, the authors do not intend to describe them here.

DRYING-OUT AND INSULATION RESISTANCE.

Before final tests are carried out on a transformer, it is essential that it be in a safe condition for those tests. This condition is that it be thoroughly dry and free from moisture. The drying-out of transformers is in reality a test of insulation resistance. By this is meant not the actual insulation-resistance value obtained from any megger reading, but the insulation characteristic with time and constant temperature.

There are many well-known ways of drying out transformers, the most satisfactory being those carried out by the circulation of dry, heated air and by the vacuum process.

Drying-out by the circulation of dry, heated air should be confined, from the point of view both of efficient drying and of the necessary time taken to ensure dryness, to transformers wound for voltages not higher than 11 000. This method is carried out in an enclosed, heat-insulated chamber fitted with a steam pipe or heating element under the floor. Air inlets are provided underneath the heating elements, and outlets are provided in the roof, thus ensuring free circulation of air.

The temperature necessary in a drying-out chamber of this description is about 80° C., and the time required varies with the size and construction of the unit, i.e. it depends on the quantity of insulation embodied therein. The length of time can be gauged from the dielectric characteristic, as shown by the curve of megger readings taken during the process. It is not essential to

take the characteristic of the insulation for all transformers dried out by this method, though, if possible, it is advisable; for if we determine the necessary time and allow a safety margin similar units may be assumed to take the same time.

It is necessary, however, to "megger" each transformer finally before withdrawing it from the drying-out chamber, i.e. at its maximum temperature, in order to ensure it being in a safe condition for the tests it has to withstand. In the case of transformers, and especially high-voltage transformers which have a high electrostatic capacity and so require an appreciable charging current, in order to ensure that a reading as reliable as possible is obtained, the megger voltage should be applied for at least 60 seconds.

A high-voltage megger is essential, i.e. one wound for 1 000 or 2 000 volts. As a guide to megger readings, when a transformer is dry the following empirical formula, in which f is the frequency, will be useful:—

$$\text{Megohms at approx. } 75^\circ \text{ C.} = \frac{\text{Kilovolts} \times 20}{\sqrt{\dfrac{(\text{kilovolt-amperes})}{f}}}$$

When the transformer is immersed in oil, its megger reading for the same degree of dryness will be much lower than when in air. This is due to the fact that when immersed in oil the resistance is the resultant of an increased number of high-resistance paths in parallel, whereas when dry the resistance is confined to the insulation in contact with the windings and the core or earth. A new transformer that has never been dried may show a megger reading of "infinity" when cold, but, when heated, the moisture that has been absorbed and may be localized is dissipated throughout the windings and insulation, thus the insulation resistance will fall to the region of zero. With the continued application of heat the dissipated moisture becomes liberated and the megger reading will gradually rise to a safe or infinite value. In general a transformer may be said to be dry if the insulation resistance is at a high or infinite value when the transformer is heated up to a temperature of 80°–85° C. For transformers for higher service voltages than 11 000 the vacuum process of drying is recommended as being the surest and quickest way of obtaining the desired result. This method is really an extension of the method already described, the drying-out being accelerated by the application of a vacuum in order that the moisture may be more rapidly vaporized and liberated.

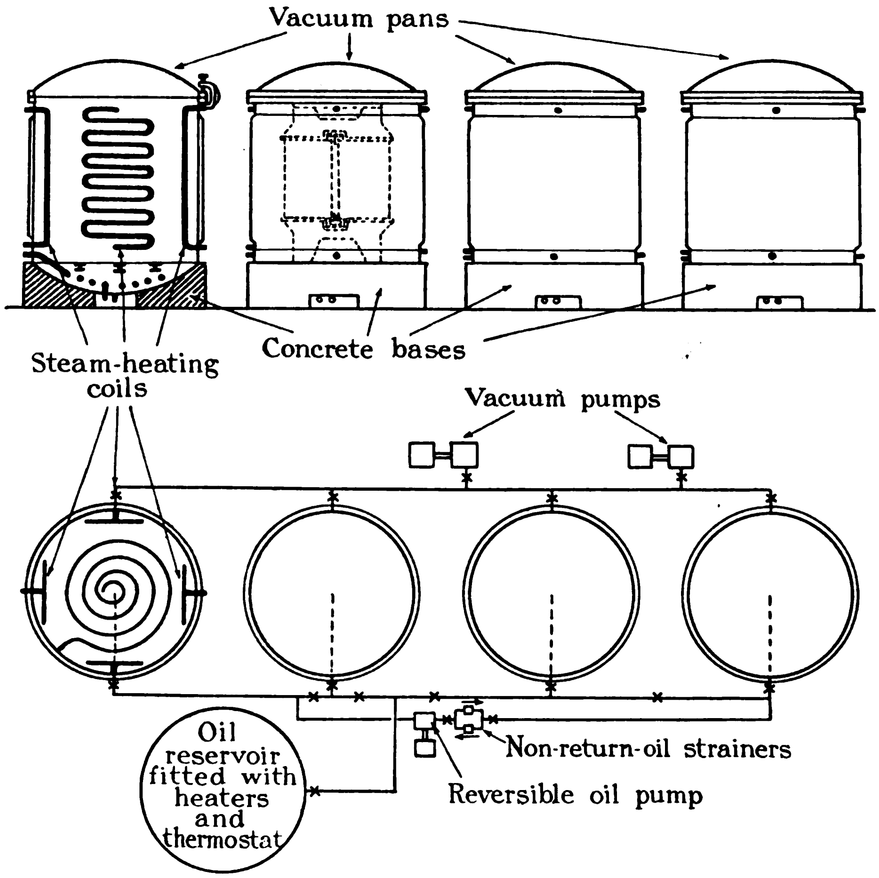


FIG. 1.—Group of vacuum pans.

Fig. 1 shows diagrammatically a system of heated vacuum chambers. The process of drying is briefly as follows:—

The transformer to be dried out is placed in the container and is connected to the insulation-resistance

terminal-board or plug. Distant-reading thermometers are fitted on or near the windings and insulation. The container is heated up to the required temperature at atmospheric pressure, and is allowed to remain in this condition until the transformer becomes uniformly heated and the insulation resistance has reached a low and constant value. This condition being reached points to the fact that the moisture has been distributed throughout the unit, as against the localized moisture in a cold unit. The cover is securely clamped down and the container and contents are subjected to a vacuum of approximately 28 inches. The vacuum type. There are two points of interest in these curves: first, the shutting down of the pump or the falling away of the vacuum is reflected in the temperature reading of the container and the flattening-out of the insulating characteristic; and, second, with the impregnation of oil the insulation resistance rapidly falls.

RATIO TESTING.

The checking of the voltage or winding ratio is the first test that should be applied to the transformer, for if it be found incorrect all other tests are of no value.

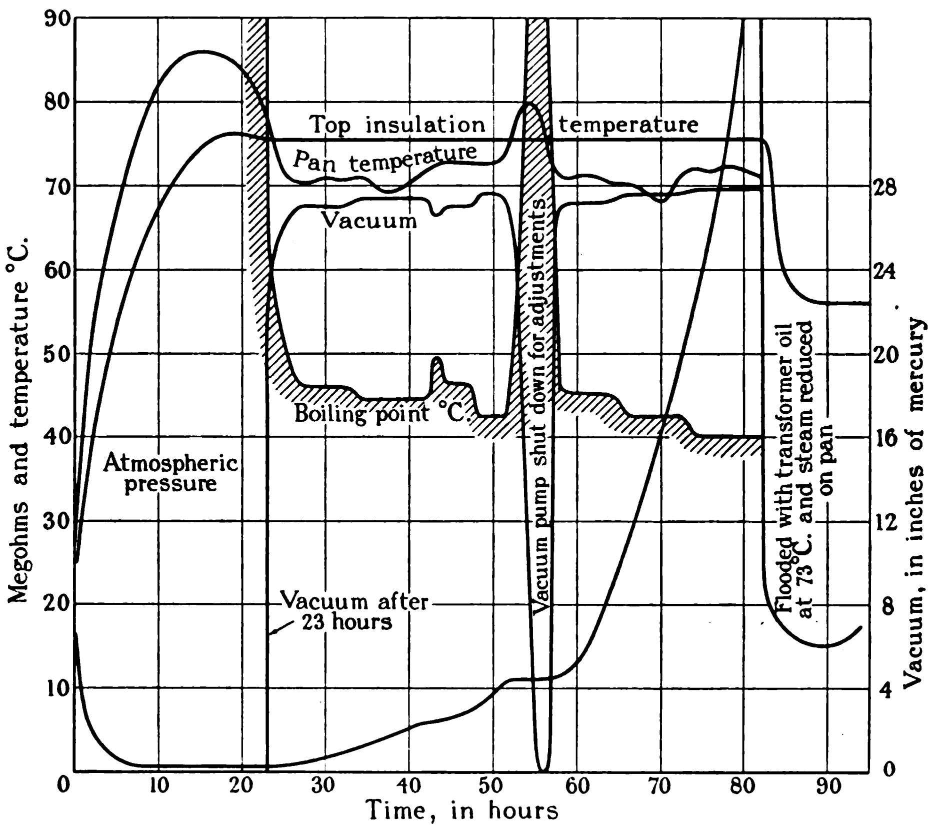


FIG. 2.—Drying-out characteristics for 125 000-volt 7 333-kVA single-phase shell-type transformer.

accelerates the drying by rapidly liberating the moisture, which is drawn off through the pump. The insulation resistance after a time begins to rise, slowly at first, and then at a gradual increasing rate until it reaches a safe or infinite value.

If oil impregnation is required it is done at this stage when dry, clean oil at a temperature approximately that of the transformer being allowed to enter under vacuum until the transformer is fully immersed. The plant is then allowed to stand in this condition until such time as full penetration of the insulation is complete. If oil impregnation is not required the vacuum must be released slowly through an air drier, to prevent moisture entering with the air.

Fig. 2 shows a typical insulation characteristic curve of a 125 000-volt 7 333-kVA transformer of the shell

There are several methods which can be employed, namely:—

(1) Voltmeter method.
(2) Standard transformer-ratio method.
(3) Resistance balance ratiometer.

The voltmeter method is self-explanatory, and is carried out by using two suitable, calibrated voltmeters, one on the primary and the other on the secondary side of the transformer under test. The accuracy of this method leaves much to be desired, on account of possible errors in reading two meters at the same instant, and also due to the fact that in many cases potential transformers have to be used, thus magnifying any error that may be present.

The standard-transformer method is carried out by

balancing the transformer under test against the standard transformer, having an adjustable ratio. This method is well known and needs no detailed description, and until the last year or two was the standard method employed by most manufacturers. The accuracy of this method varies according to the size of the transformer under test and the voltage for which it is designed. For instance, high-voltage transformers having a large capacity take an appreciable charging current, and hence, as this method is a null one, errors within limits are quite possible.

Resistance-balance ratiometers are now generally employed and give reliable results in all cases. Such instruments can be purchased as standard instruments.

Fig. 3 shows diagrammatically a typical resistance ratiometer which compares the ratio of the transformer under test with a resistance bridge. The high-tension winding of the transformer is connected across a resistance R, tapped to suitable dial switches arranged to give various resistance values. The low-tension winding is connected in opposition across a part of

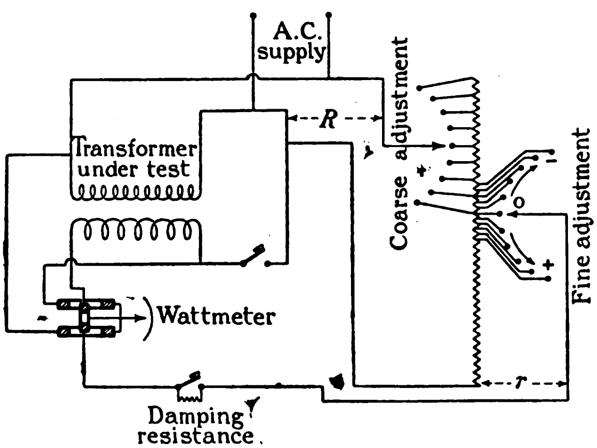


FIG. 3.—General arrangement of a resistance ratiometer.

this resistance R, also tapped through suitable dial switches to a sensitive wattmeter movement to show the balance of the two circuits the field coils of which are excited off the high-tension supply. By this arrangement any current flowing in the low-tension windings will be indicated by a wattmeter reading. The procedure is so to adjust the dial switches as to obtain a true balance and a zero reading on the meter. The ratio of the transformer is then R/r.

There are several modifications of this type of instrument, but all function on the same principle. In general, this type of ratiometer has superseded the other methods mentioned, as it is not subject to the same inherent errors, and accuracy can be obtained over a much wider range.

Polarity Testing.

The polarity test confirms the relation of the windings to one another, and is the only means of accurately determining the connection of transformers for parallel operation or connecting in banks.

Apart from a visual examination of the rotation of the windings, there are several ways of obtaining the required result. The polarity can be readily obtained by comparison with a transformer of known polarity, and can be carried out at the same time as the ratio test if the standard-ratio transformer be suitably marked.

Another method is that of employing a single-phase eddy-current wattmeter, the direction of rotation of the eddy-current disc indicating the polarity.

Still another method is that of using direct current. A direct current is passed through the high-tension winding and a voltmeter is connected across its terminals to give a positive deflection. The voltmeter leads are then transferred to the low-tension windings, the individual leads being changed over in a definite way according to the standard of polarity. A break in the current in the high-tension winding produces a kick on the voltmeter, now on the low-tension side, due to the momentary induced voltage, and the direction of the kick will denote the polarity.

Iron Loss and Magnetizing Current.

The accurate measurement of iron loss and magnetizing current is essential, as this loss is in most cases constant and, therefore, important to the customer, from the point of view of running costs. The iron loss and magnetizing current are measured by supplying the normal voltage at the correct frequency to one winding of the transformer, with the other open-circuited, as shown in Fig. 4. The voltage and fre-

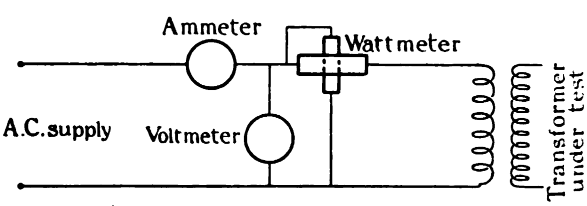


FIG. 4.—Simple single-phase iron-loss connections.

quency are adjusted to the correct values for the particular winding. The wattmeter reading then gives the iron loss and the ammeter reading the no-load current, often mistakenly termed the "magnetizing current." The no-load current is made up of a watt component due to the energy loss and a wattless component due to the magnetization, and, as the power factor can be obtained, the wattless or magnetizing current can be calculated.

With large transformers the magnetizing current is almost equal to the no-load current, but with small transformers there is an appreciable difference. The no-load power factor varies according to the size and frequency of the transformer under test, and comes within the range of 0·2 to 0·06 approximately. This necessarily results in small readings on the wattmeter and, therefore, the possibility of errors in reading.

To overcome these inaccuracies of reading, or to reduce them to a minimum, it is essential that a wattmeter be used suitably designed for low-power-factor work. Such meters are available and the authors have had them in constant use for some considerable

time with satisfactory results. One such instrument has its maximum capacity in volt-amperes equal to five times the maximum scale reading in watts, and this means that, compared with an ordinary wattmeter for unity power factor, the scale reading will be five times as great and, consequently, the error in scale reading only one-fifth.

Wattmeters are generally so connected in the circuit that the pressure coil of the instrument is on the supply side, or between the supply and the current coil, thus introducing small errors due to losses in leads, joints and instrument coils. The low-power-factor wattmeter is fitted with a compensating device to neutralize the effect of the current taken by the pressure coil passing through the current coil. This enables the pressure terminals of the wattmeter to be connected directly across the terminals of the transformer under test. For three-phase iron-loss measurements several instruments are necessary, unless some special change-over device is used for putting the same instruments in the different phases in turn. Two well-known methods of measurement are available, namely, the two-wattmeter and three-wattmeter methods, each of which gives accurate results provided suitable instruments are used.

Fig. 5 shows the instruments and connections necessary for the three-wattmeter method, and Fig. 6 those for the two-wattmeter method. Unity-power-factor wattmeters are permissible when using the two-wattmeter method, but low-power-factor meters are essential for the three-wattmeter method. To illustrate the above, Table 1 gives figures for a 200-kVA transformer tested by the two methods, and it can be clearly seen that the meter power-factors are much higher for the two-wattmeter than for the three-wattmeter method.

ment for the two-wattmeter method, and Fig. 8 an arrangement suitable for both methods of measurement. In all change-over switch arrangements the

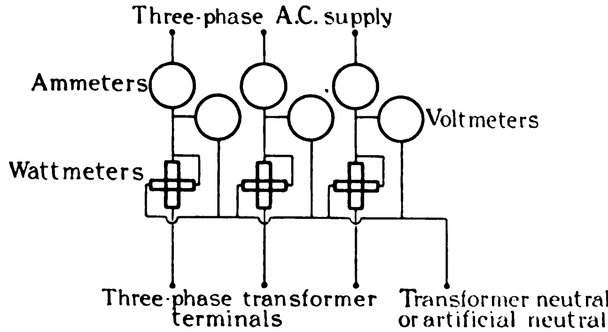


Fig. 5.—Three-wattmeter method of measuring three-phase iron loss.

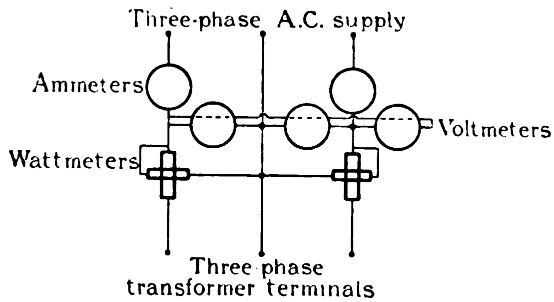


Fig. 6.—Two-wattmeter method of measuring three-phase iron loss.

inclusion of an additional voltmeter for checking and so maintaining the voltage of supply at a constant value during the test is advisable. The special arrangement for earthing the instruments automatically as the switches are changed over should be noted.

Table 1.

Iron-loss Tests on a 200-kVA 40-Period Three-Phase Transformer.

	Line volts	Amps.	Meter kW	Meter kVA	Meter power factor	Overall power factor
Two-wattmeter method	440	10	3·12	4·400	0·706	0·153
	440	8·5	—	—	—	
	440	10·2	−2·0	4·480	0·447	
	Phase volts					
Three-wattmeter method	$440/\sqrt{3}$	10·2	0·62	2·595	0·237	0·153
	$440/\sqrt{3}$	10·0	0·16	2·542	0·063	
	$440/\sqrt{3}$	8·5	0·34	2·16	0·1535	

In connection with the three-wattmeter method, if used for delta-connected transformers it is necessary to create an artificial neutral. This neutral may be the neutral point of the a.c. supply, the neutral point of another transformer across the same supply, or the neutral of a bank of three resistances or choke coils.

In order to reduce to a minimum the number of instruments in use, special change-over switches can be arranged suitable for both methods of measurement. Fig. 7 shows a change-over switch arrangement for the two-wattmeter method, and Fig. 8 …

For high-voltage iron-loss testing, provision has to be made for the insertion of potential transformers, but as the ammeter and current coil of the wattmeter are always earthed, no current transformers are necessary. This tends to more accurate results, due to the elimination of errors brought about by phase-angle displacements such as are present when they are used.

Temperature measurements are usually not necessary, though advisable. The corrections for temperature are

so small that they are generally neglected. This point is described in detail later.

Easy and accurate measurement of frequency is of vital importance in transformer testing, for more than 25 per cent of inaccurate results can be traced to insufficient care in obtaining a true reading.

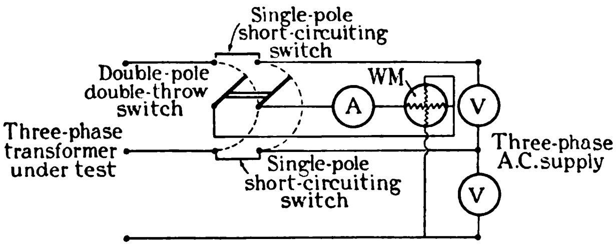


FIG. 7.—Change-over switching for 2-wattmeter method.

Several methods may be used, but the one recommended is a series of frequency meters of the electromagnetic type, connected to slip-rings off the armature of the d.c. driving motor. This is necessary, as the instrument is dependent on voltage and is accurate

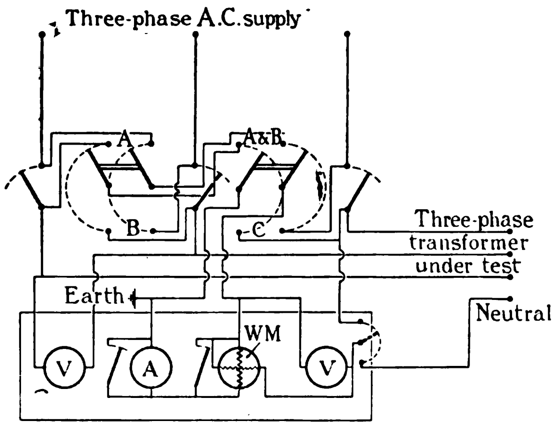


FIG. 8.—Change-over switching for 3-wattmeter method.

within certain voltage limits. If the frequency is measured by meters on the a.c. side of the motor-generator set, it would be necessary to include variable-resistance or multiple-ratio transformers to compensate for the varying voltages that the machine has to supply. The

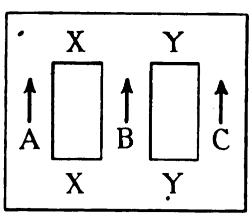


FIG. 9.—Flux diagram for core-type frame.

d.c. voltage for the driving motor is usually constant within limits, so that tappings from the armature windings to slip-rings provide the ideal conditions.

Several advantages can be claimed for this method. For instance, by using a relay the instrument can be easily connected to any measuring table; the instruments can be used for several machines, and the range of frequencies measured can be limited, a wide scale being provided for a small variation in frequency.

Belted or driven tachometers should be provided for each machine, for checking and for starting up the sets, but the final adjustment can be made on the various measuring tables.

THREE-PHASE CORE-TYPE TRANSFORMERS.

When measuring the iron loss of three-phase core-type transformers by the three-wattmeter method the losses measured in the three phases are never equal,

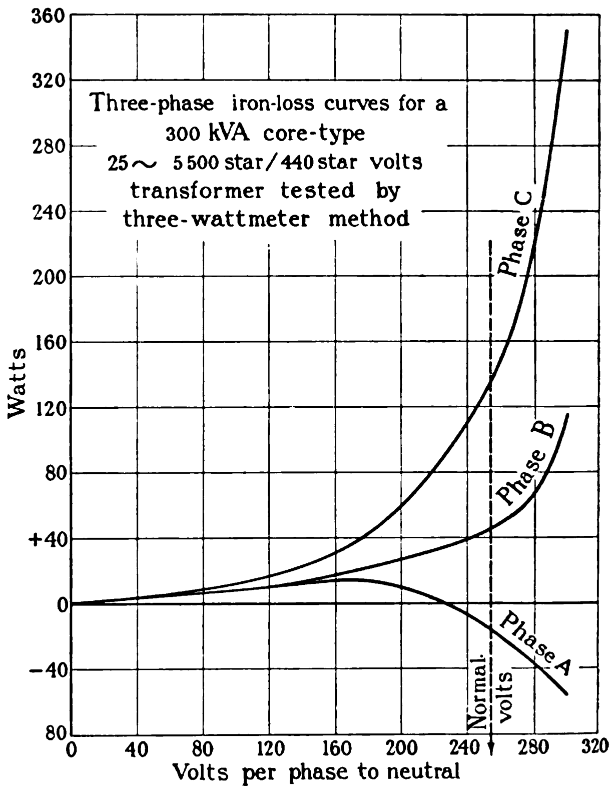


FIG. 10.

and in some instances a negative reading is obtained in one of the outer phases. This apparent anomaly is puzzling to many, but it can be accounted for by the unbalancing of the magnetic flux in the core, due to its shape. If we consider a transformer similar to Fig. 9, then by applying a symmetrical three-phase voltage to the three phases, we excite each limb to the same flux density. Half the flux in limb B returns through limb A, and half through limb C, because from the point of view of phase B the core is symmetrical. The flux in limb A returns part by limb B and part by limb C, but due to the fact that the reluctance of the return path through B is lower than that through C more flux will pass through B than through C. Similarly the flux in C will return in like manner through B and A. Supposing the reluctances of these paths are in the ratio of 60 to 40, then 60 per cent of the flux

from A will return through B and 40 per cent through C, and similarly 60 per cent of the flux from C will return through B and 40 per cent through A.

The reason for the unequal loss measurements is found in the unequal distribution of the return flux, and a concrete example will make it more clear.

Details of a test taken on a three-phase 300-kVA 25-period core-type transformer by the three-wattmeter method are given in Table 2.

between the no-load current and voltage in phase A must be greater than 90°.

Fig. 11 shows this relation graphically, and has been drawn up from the above test figures, with certain assumptions. The no-load currents have been taken as a measure of the reluctance, though this is not strictly true owing to their watt components. The reluctance of the return paths for flux B is proportional to 6·6 in A and 6·6 in C; the reluctance of the return paths for flux A is proportional to 6·6 in B and 11·8 in C; and the reluctance of the return paths for flux C is proportional to 6·6 in B and 11·8 in A. Whilst the above relation of reluctances is not strictly true, it is of the right order and gives the result required, which is that attaining to a phase angle greater than 90°, and thus a negative wattmeter reading.

TABLE 2.

Volts, per phase	No-load current, amperes			Kilowatts			Kilovolt-amperes			Phase power factor		
	C	B	A	C	B	A	C	B	A	C	B	A
300	58·8	52·0	57·5	3·52	1·16	— 0·56	17·65	15·6	17·25	0·2	0·0745	0·0325
280	33·0	24·8	33·8	2·19	0·644	— 0·384	9·25	6·95	9·46	0·237	0·0925	0·0406
254*	18·4	13·2	18·4	1·364	0·458	— 0·164	4·65	3·35	4·68	0·293	0·1368	0·0350
230	12·5	8·8	12·0	0·964	0·350	— 0·02	2·87	2·02	2·76	0·336	0·1732	0·00726
220	10·4	7·0	10·4	0·8	0·312	0·02	2·29	1·54	2·29	0·35	0·2025	0·00873
180	4·9	3·55	4·9	0·422	0·212	0·132	0·882	0·64	0·882	0·478	0·331	0·1495
140	2·7	2·0	2·7	0·233	0·132	0·122	0·378	0·28	0·378	0·616	0·472	0·323

* Normal volts.

Fig. 10 shows a characteristic curve of loss measurements in each phase, plotted against the applied voltage. The curve for phase C shows an increasing loss with voltage, and similarly phase B, but phase A shows an increase and then a decrease, and finally a negative reading for higher voltages. The extent of the negative value depends on the induction in the core at normal voltage, and also on the relation of the reluctances of the two magnetic paths for the flux in limbs A and C. This negative reading also means that the phase angle

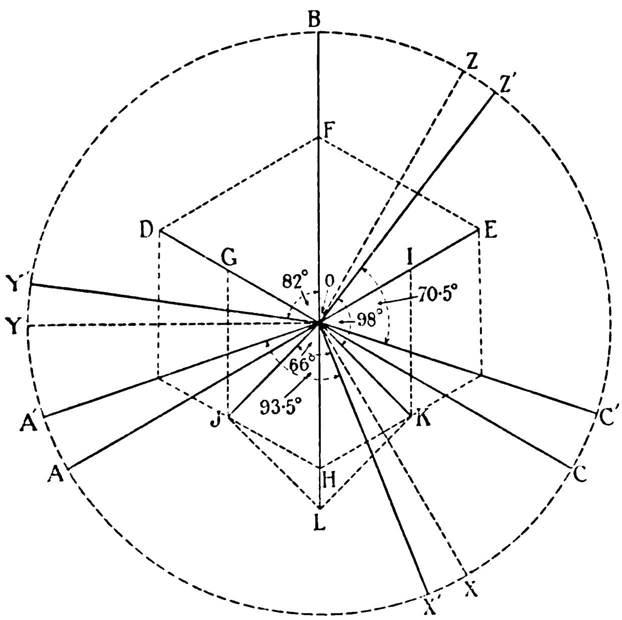


FIG. 11.—Vector diagram for three-phase core-type unbalanced magnetic circuit.

In the diagram,

- OA, OB and OC represent the main flux in limbs A, B and C.
- OD represents the return flux of C through limb B.
- OE represents the return flux of A through limb B.
- OF represents the resultant flux of C and A through limb B.
- OG represents the return flux of C through limb A.
- OH represents the return flux of B through limb A.
- OJ represents the resultant flux of C and B through limb A.
- OI represents the return flux of A through limb C.
- OH represents the return flux of B through limb C.
- OK represents the resultant flux of A and B through limb C.
- OL represents the resultant flux of OJ and OK and is equal and opposite to OF.

The main flux being 90° behind the applied voltage, OX, OY and OZ represent the applied voltage, and if there were no watt component in the no-load current the angles between OF, OJ, OK and the applied voltage would represent the phase angle of the return flux, but owing to the watt component the angle of 90° is reduced. From the test figures we know the phase angles and, taking the one for the symmetrical phase, which is 82°, OX′, OY′, OZ′ represent the applied voltage at an angular displacement of 8° from OX, OY and OZ.

The no-load current, though dependent on the return

flux, is not in phase with it, for the current is proportional to the reluctance of the magnetic circuits whilst the flux is inversely proportional to it. The resultant of OD and OH gives the phase position of no-load current OA′ in phase A, and the resultant of OE and OH gives the phase position of the no-load current OC′ in phase C. The phase angles of the no-load current relatively to the applied voltage are equal to 82°, 93·5° and 70·5°, and are approximately equal to those obtained from the test results and are in the same rotation. It will also be noticed that the sum of the angles from the diagram is 246° and from the test figures 247°. The slight variation in the values of the angles is due to the assumption already mentioned, but the result proves the possibility of a lag greater than 90°, and hence a negative reading on a wattmeter in one outer phase of a three-phase core-type transformer.

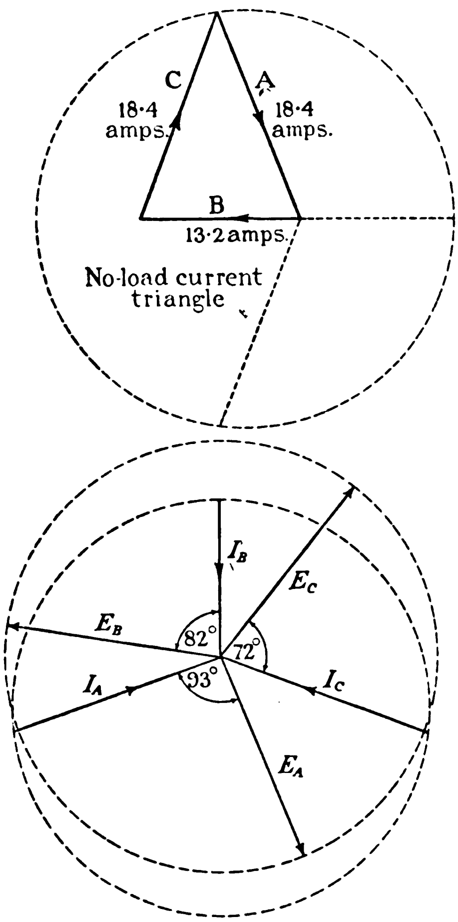


Fig. 11A.—No-load current and voltage vector diagram for three-phase core-type transformer.

Fig. 11A shows the vector diagram at normal voltage for the test example taken. The no-load currents form a closed triangle, and as the currents are unequal the angles between them must be unequal. As the reluctance of the return path for the magnetic flux of phases A and C increases, so will the negative value increase due to the increase of the angle between the currents in phases A and C. The shorter the length of the core, the greater will be the divergence of the current vectors. Although a negative reading is obtained it must not be assumed that there is no energy loss in that particular phase. The method of measurement and the result of the phase relation of the starred currents produce the effect obtained.

Iron Loss and Form Factor.

The iron loss of any particular transformer may be directly measured by the method already described, but unless the wave-form of the applied voltage be a sine wave the results will be greater or less than the estimated or correct loss. If the wave-form be peaked, having a form factor (R.M.S. volts divided by average volts) greater than 1·11, then the measured loss will be lower, whilst if the wave-form be flat with the form factor less than 1·11 the measured loss will be too high. In general the wave-form will be peaked, due to the nature of the load on the machine, and the measured losses will be of a low order. Since the form factor of the wave does not affect the eddy loss in the same manner as the hysteresis loss it is necessary, if a correction is to be made, to separate the loss into its two components and correct the hysteresis loss in line with the form factor.

Table 3 shows the effect of form factor on hysteresis loss, the effect at a form factor of 1·11 being taken as 100 per cent.

Table 3.

Form factor	Relative hysteresis loss
	per cent
1·0	118
1·05	109
1·11	100
1·15	94·5
1·2	88·2
1·3	77·6
1·4	69·3

When it is remembered that the hysteresis loss forms by far the greater proportion of the total loss, any increase in form factor will appreciably reduce the measured loss and so give erroneous results.

Before passing on to the ways and means of carrying out this correction, it would be well to point out that the iron loss in service will rarely be that for a pure sine wave, especially for large units, but for a basis of standard reference and comparison the loss as measured should be that obtained for a sine-wave voltage or should be corrected for such a wave.

The correction for form factor may be accomplished in two ways :—

(1) By obtaining the form factor of the applied voltage and correcting the hysteresis loss in line with the form factor.

(2) By applying an equivalent voltage to compensate for the form factor by means of an instrument termed an iron-loss voltmeter.

To carry out the correction for form factor by method (1), it is essential to obtain the correct wave-

form of the applied voltage, or its form factor. This can be done by means of the oscillograph, thus obtaining a true picture of the wave and then analysing it for the form factor. The form factor can also be obtained by fixing a commutator or mechanical rectifier to the machine giving the a.c. supply, or it may be obtained

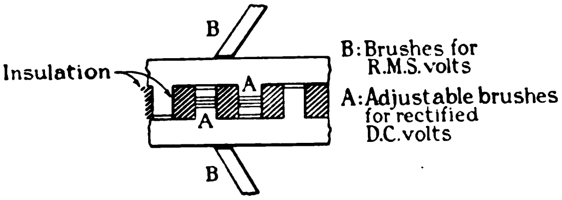


FIG. 12.—Plan of simple commutator rectifier.

by the authors' arrangement of thermionic valve rectification. The mechanical means of obtaining the form factor is by a special commutator, shown in Fig. 12, fitted on the alternator shaft.

This type of apparatus is not recommended as a commercial test instrument owing to the great care

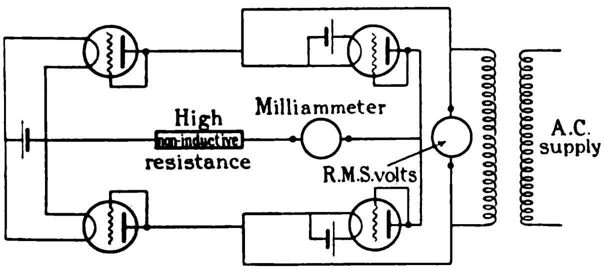


FIG. 13A.—Four-valve full-wave rectification.

that has to be exercised in setting it. Another disadvantage is that each alternator used has to be fitted with a special commutator, and, further, the method is quite impossible when the a.c. supply is taken from a.c. mains and not from a definite machine.

In considering the question of form factor and the

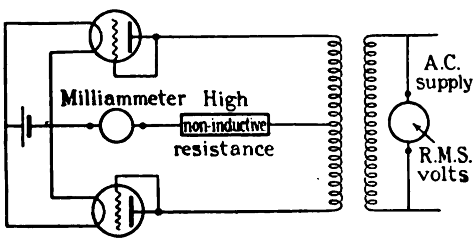


FIG. 13B.—Two-valve full-wave rectification.

method of obtaining it without having recourse to mechanical means, the authors have carried out many experiments and have obtained a scheme of apparatus which gives very reliable and consistent results. The methods employed cover the rectification of the complete a.c. voltage wave by means of either two or four three-electrode thermionic valves. Fig. 13A shows the connections of the four-valve full-wave rectification, and Fig. 13B that for the two-valve full-wave rectification. The valves are connected in bridge form, and across the bridge the rectified direct current is caused to flow through a standard, high, non-inductive resistance and a milliammeter, thus giving a means of obtaining the rectified voltage or the average a.c. voltage.

To obtain satisfactory results, a straight-line characteristic had to be aimed at for valve impedance plotted against circuit voltage. By maintaining the filaments at a constant, normal temperature and the external resistance at a high value relative to the internal resistance of the valves, the working part of the characteristic was approximately a straight line. It was found that the valves most suitable were those of low impedance, and to reduce still further their impedance the grid was connected to the plate. Using an external resistance of 104 310 ohms, it was found that as the voltage across the valve outers was increased, the valve impedance decreased rapidly and became constant or asymptotical at 160 volts, or approximately 5·6 volts (d.c.) across the valves. With four-valve rectification, two valves were used in series for each half-wave rectification, and, with the valves used, their impedance became constant at 4 000 ohms.

With two-valve full-wave rectification the mid-point of the transformer was used as the bridge point, and the results obtained were more accurate than those obtained by the four-valve method. The former is therefore recommended as the most suitable.

In this particular method with a grid connected to the plate, the valve impedance became constant, or asymptotical, at 3 000 ohms, with 150 volts across the valve outers, i.e. with 75 volts across the valve and resistance. The same resistance of 104 310 ohms was used and the d.c. voltage across the valves was 5·5 volts.

For these experiments two B.T.H. B4 valves were used, but any low-impedance receiving valve of the three-electrode type is suitable, provided the circuit voltage for constant valve impedance is ascertained and the voltage is maintained at not less than this value.

The original experiments were conducted with an ordinary potential transformer with a mid-point tapping, but it was found that the d.c. component affected the R.M.S. voltmeter so that the R.M.S. voltage was measured on the primary side as shown in the diagram.

On testing the apparatus on a machine specially designed to give a sine wave-form of voltage, the actual form factor was given correctly when allowance had been made for the valve impedance, which is constant for a particular valve.

Many tests were taken as checks on distorted waves, and the form factors obtained corresponded almost exactly to that obtained from the actual wave as recorded by an oscillograph.

The authors claim the tests to be accurate within 0·5 per cent by the method described. In addition to obtaining the form factor, the losses measured must be separated into the two components, hysteresis and eddy loss, because, since the form factor affects only the hysteresis loss, that component must be obtained.

Separation of Losses.

The separation of losses as given by the measured loss can be carried out by several methods :—

(*a*) Measure the loss at constant induction and varying frequency and draw the curve showing the relation between loss and frequency. The tangent to the curve gives the dividing line of the losses, i.e. the ordinate between the datum line and the tangent is the hysteresis loss, and that between the tangent and the curve is the eddy-current loss.

This method is not recommended, owing to the difficulty in drawing a true tangent and also in obtaining losses at low frequencies, which is essential if a true curve is to be plotted.

(*b*) Measure the loss at varying induction and constant frequency and draw a curve showing $W/E^{1\cdot 6}$ plotted against $E^{0\cdot 4}$, which should be a straight line. The ratio of the ordinate at the vertical axis to the ordinate at normal voltage gives the ratio of hysteresis loss to total measured loss.

(*c*) Measure the losses as in (*a*) and plot loss/frequency against frequency. This should be a straight line, and the ratio of the ordinate at the vertical axis to the ordinate at normal frequency gives the ratio of hysteresis loss to total measured loss.

(*d*) Measure the loss at constant voltage and varying frequency and plot it against $1/f^{0\cdot 6}$. This should be a straight line, and the point where it cuts the vertical axis gives the eddy-current loss in watts.

Methods (*c*) and (*d*) are recommended as being likely to give the most accurate results, and of these methods (*c*) is the simpler and quicker, which is a great asset to test-bed work.

Having obtained the hysteresis component and the form factor, the hysteresis loss should be multiplied by

$$\frac{(\text{Form factor})^{1\cdot 6}}{(1\cdot 11)^{1\cdot 6}}$$

Various opinions are still held as to the value of the index in the expression for hysteresis, especially at high inductions. Some authorities give it as 1·68, whilst others say that it is 2.

The test-bed not being a laboratory, the authors have retained the original constant in their calculations, and this is supported by the test results obtained from the analysis of test curves for samples of transformer iron taken at random. Results were obtained by the above loss-separation methods on a 7 500-kVA single-phase shell-type transformer for 25 frequency, and it will be noticed that from a commercial-test point of view there is little variation in the results obtained :—

	per cent	per cent
Method (*a*)	Hysteresis loss 81 ;	eddy loss 19
Method (*b*)	Hysteresis loss 80·7 ;	eddy loss 19·3
Method (*c*)	Hysteresis loss 80·9 ;	eddy loss 19·1
Method (*d*)	Hysteresis loss 81·6 ;	eddy loss 18·4

As examples of corrected measurements the following tests were taken on two large transformers, one designed for 25-period service and the other for 50-period service.

25-Period Example.

7 500-kVA single-phase shell-type 33 000/5 500-volt transformer.
Form factor of applied voltage = 1·4.
Estimated loss with normal voltage for sine wave = 24 000 watts.
Measured loss with normal voltage for a form factor of 1·4 = 17 850 watts.
Separation of measured loss gives 80·9 per cent hysteresis and 19·1 per cent eddy loss.
Hysteresis loss corrected for form factor = 116·31 per cent of measured loss.
Total corrected loss in watts = 24 200.

Hysteresis loss corrected = 86 per cent.
Eddy loss corrected = 14 per cent.

50-Period Example.

7 833-kVA single-phase shell-type 136 000/6 600-volt transformer.
Form factor of applied voltage = 1·25.
Estimated loss with normal voltage for sine wave = 32 000 watts.
Measured loss with normal voltage for form factor of 1·25 = 27 750 watts.
Separation of measured loss gives 76·1 per cent hysteresis and 23·9 per cent eddy loss.
Hysteresis loss corrected for form factor = 92 per cent of measured loss.
Total corrected loss = 115·9 per cent of measured loss.
Total corrected loss in watts = 32 150.

Hysteresis loss corrected = 79·4 per cent.
Eddy loss corrected = 20·6 per cent.

These typical examples show how necessary it is, even if only for the designer's information, that the form factor should be ascertained correctly or in some measure compensated for.

As a check on the above corrected losses and the percentage hysteresis and eddy loss, it is interesting to compare them with the percentage losses on a sample of iron at the same induction.

At 25 frequency, loss for sample = 88·5 per cent hysteresis and 11·5 per cent eddy loss.
At 25 frequency, loss for transformer = 86·0 per cent hysteresis and 14·0 per cent eddy loss.
At 50 frequency, loss for sample = 82·0 per cent hysteresis and 18 per cent eddy loss.
At 50 frequency, loss for transformer = 79·4 per cent hysteresis and 20·6 per cent eddy loss.

These comparative figures show conclusively that the corrected losses are in order, and also that the corrected measured losses are sufficiently accurate for commercial purposes. The slight variation in percentage in the corrected loss for the sample can be accounted for by the difference in pressure exerted on the punchings in

the transformers and sample, or by the building-in of a few more or a few less core punchings to that called for by the design.

The second method of correction for wave-form, namely, that of applying a compensated voltage value in line with the form factor, is simple and easy in operation, but depends entirely on the calibration of an instrument termed an iron-loss voltmeter. This type of meter is used by the American Westinghouse Co., and apparatus based on a similar principle is also used by the General Electric Co. of America. In brief, the so-called voltmeter indicates an equivalent voltage for a sine wave-form of applied voltage.

ratio of the two readings will be some measure of the difference in form factor.

Fig. 14 shows the internal connections of the iron-loss voltmeter and also its position in the iron-loss test-circuit.

Table 4 gives the results of tests taken with this type of instrument. These show clearly the increase in voltage necessary and also the error in the correction for loss measurement. The results are also compared with the correction method as previously explained, by correcting for form factor. The similarity, or almost equality, in the results obtained by the two methods is worthy of attention.

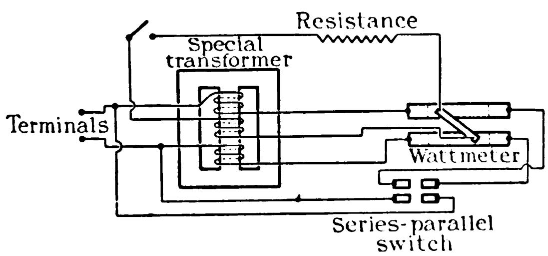
TABLE 4.

Test taken on a Large Single-phase Transformer at Normal Voltage (24 300).

Frequency	Voltage		Form factor	Loss		Normal volts measured on
	R.M.S.	By iron-loss voltmeter		Total measured	Corrected	
60	24 300	23 600	1·192	50 500 W	55 300 W	R.M.S. voltmeter
60	25 200	24 300	1·195	55 200 W	—	Iron-loss voltmeter

The voltmeter consists of a wattmeter movement permanently connected so as to read the loss of a standard transformer incorporated in the instrument. The meter is calibrated on a pure sine wave and the scale is marked in volts against the watt loss measured at various voltages. The dial also carries a watt scale, so that the watt loss in the meter may be taken care of in the corrected measurements. The accuracy of the instrument depends on the design of the standard transformer incorporated in it, and on its calibration

Special machines could be designed to give a better wave-form under the special conditions of loading, as occurs with iron-loss testing, but as the test load necessarily varies according to the size of the transformers under test, a wave-form to suit all such variable conditions would be impossible. Usually the wave-form on open-circuit conditions is as near as possible a sine wave, the distortion, which is due to the condition of loading, being compensated for by the method described above.



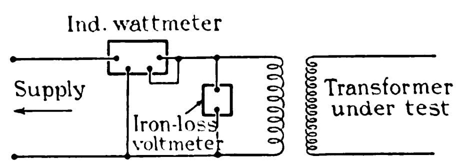


FIG. 14.—Internal connections of iron-loss voltmeter, and diagram of connections for testing.

on a true sine wave. When in use for testing iron loss, it is connected up in the same way as a standard voltmeter. A wattmeter is also connected in the circuit in such a way as to measure the total input of the transformer under test and the loss in the iron-loss voltmeter. The applied voltage is then adjusted at the correct frequency until the iron-loss voltmeter reads the normal supply voltage. The total power input is read on the wattmeter and the iron-loss voltmeter, and the difference between these two readings gives the true loss on the sine-wave voltage. If an ordinary voltmeter be also connected in circuit, this will give the actual effective voltage applied, and the

IRON-LOSS CORRECTION FOR TEMPERATURE.

Temperature has very little effect on the iron-loss measurements and is usually neglected. The permissible correction is that for the eddy-current loss component of the losses, which may be corrected for temperature. The eddy-current loss decreases slightly with increase in temperature, depending on the temperature coefficient of resistance, which for transformer iron is approximately 0·00077 between 20° C. and 100° C. In other words, the eddy-current loss may be reduced by 0·077 per cent for every degree increase of temperature. Thus, if the iron-loss measurements were taken at 20° C. and have to be corrected for

by 75° C., the eddy-loss component must be reduced by 4·23 per cent. As the eddy-current loss varies from approximately 15 per cent for 25-period, to 20 per cent for 50-period transformers, the adjustment for a temperature-rise of 55 degrees C. would mean a reduction of 0·634 per cent and 0·85 per cent in the total iron loss for 25- and 50-period transformers respectively.

As will be seen from the above figures, the permissible correction for temperature is very small and is rarely used, as it is within the possible errors of measurement due to visual, frequency, ratio, and meter errors.

Copper or Load Loss and Impedance Tests.

The measurement of copper loss is usually carried out by an arrangement of instruments similar to that used for iron-loss measurements, except that the one winding of the transformer, usually the l.t. winding, is short-circuited, and a supply capable of circulating the full-load current at the correct frequency is connected to the other winding, as in Fig. 15. The ammeter and wattmeter must be suitable for carrying the full-load current for the particular winding on which the loss is measured, but the voltmeter has only to measure the impressed or impedance voltage necessary to circulate the current, and this can be approximately ascertained from the design data.

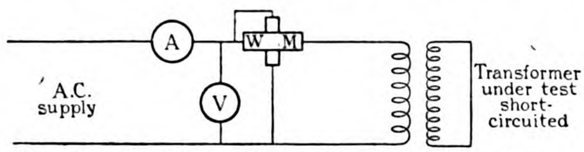


Fig. 15.—Simple copper-loss diagram of connections.

The measured loss is composed of two losses—that due to the ohmic resistance of the copper and that due to the stray losses termed eddy-current losses. The ohmic-resistance loss is the product of the ohmic resistance and the square of the current, being the arithmetical sum for the two windings. The stray losses are brought about by induced currents flowing in small local circuits within the copper windings, terminal straps and surrounding metal, and generally depend on the strength and extent of the leakage fields. This loss is proportional to the square of the frequency and to the resistivity of the particular metals.

The ratio of the ohmic loss to the eddy loss varies for different transformers, being dependent on the characteristics of the transformers, such as their reactance, current and copper section. High reactance and heavy currents are conducive to eddy-current losses. The separation of the losses can be carried out by two methods :—

(*a*) By calculating the ohmic loss from the measured resistances of the transformer windings and subtracting this loss from the measured loss, which gives as a result the eddy-current or stray losses.

(*b*) By separation of the losses. This is carried out by taking several readings of watts loss and frequency, keeping the load constant. The watts loss plotted against the square of the frequency is a straight line, and the loss at zero frequency is the true ohmic loss.

The applied voltage measured on the copper-loss test is termed the impedance voltage, and is usually given as a percentage of the rated voltage at a definite temperature.

When taking copper-loss measurements on three-phase transformers it is advisable to take three-phase measurements, i.e. to apply three-phase currents. Especially is this the case for transformers having a high internal reactance, as the eddy currents tend to become unbalanced and excessive when measured single-phase.

For carrying out these tests, measuring tables such as those described under "Iron-loss Testing," can be used. Low-power-factor wattmeters are desirable, as the actual readings on the meters are low on this test if the three-wattmeter method of measurement be used. Single-phase measurements with all three phases connected in series, either in open delta or Z connection, are liable to excessive errors and should not be used except for three single-phase transformers to make up a three-phase group. The test-figures in Table 5, taken on the same transformer, show the extent of the errors that may be obtained. The tests were taken on a large three-phase core-type transformer having 20 per cent impedance, obtained by inserting magnetic shunts between the windings.

Table 5.

Method	Phase volts			Amperes			Wattmeter reading $K = 60$			Total watts
	A	B	C	A	B	C	A	B	C	
3-phase measurement with 3-phase supply	3 030	3 042	3 072	72·3	72·7	73	142	163	172	28 620

	Total volts	Amperes	Wattmeter reading $K = 200$	Total watts
Single-phase, 3 phases in series or Z connection	8 930	72·2	149	29 800
Single-phase, 3 phases in open delta	7 000	72·2	242	48 400

All the above measurements were carried out on the h.t. windings with the l.t. side short-circuited, each phase separately, and the figures provide a very good reason why it is impossible to run high-reactance transformers on load by single-phase circulation either in open delta or Z-connected, as referred to later under full-load temperature runs. With transformers having magnetic shunts inserted between the h.t. and l.t. windings to increase the reactance, it is necessary that a curve of impedance should be taken up to a high value of overload to prove that the magnetic shunt does not become saturated within the loading limits and that the impedance at the higher values does not deviate from the straight line beyond the permitted tolerance.

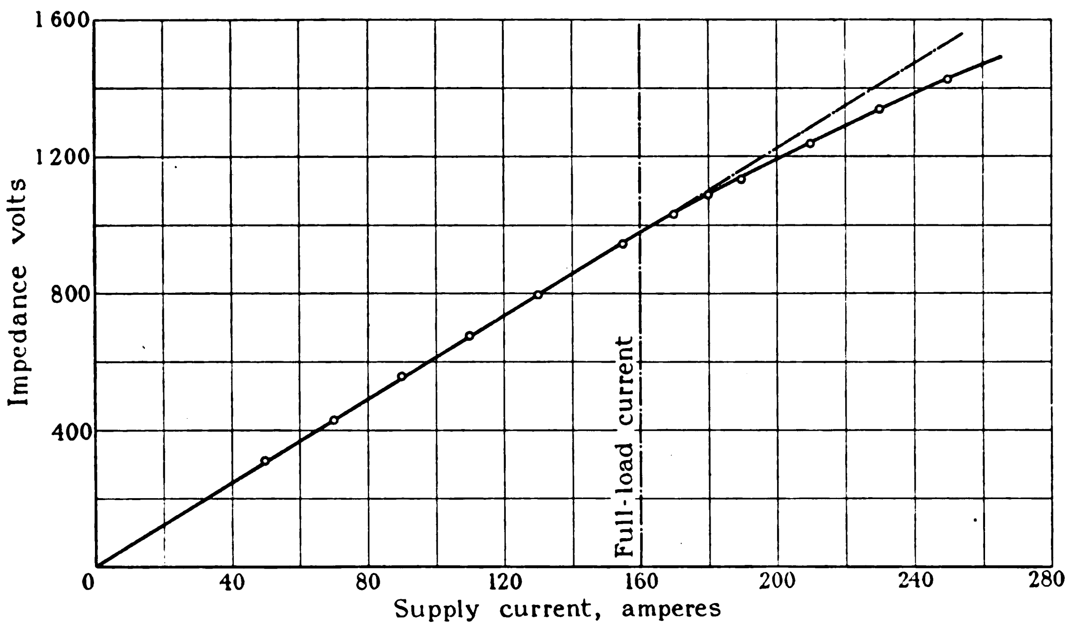


FIG. 16.—Curve showing the saturation of magnetic shunts on highly reactive transformers.

A typical example is shown in Fig. 16 for a large three-phase core-type transformer having 18 per cent internal reactance. On this particular transformer a straight-line characteristic of impedance was maintained up to 11 per cent overload, and deviated only by 5·1 per cent at 50 per cent overload.

Correction of load loss or copper loss for temperature.—The copper loss of a transformer is usually given, and is guaranteed at a specific temperature, but it is rarely possible to obtain the actual reference temperature on test, so that corrections have to be made to arrive at the copper loss for comparison with the guarantee.

This correction for the ohmic loss is an increase proportional to the temperature, and for the eddy currents or stray loss is a decrease in proportion to the temperature, assuming all the losses to be induced in the copper. The correction for ohmic loss is :—

$$\frac{\text{Ohmic loss at temperature } T}{\text{Ohmic loss at temperature } T_0} = \frac{234\cdot5 + T}{234\cdot5 + T_0}$$

The correction for eddy-current loss is :—

$$\frac{\text{Eddy-current loss at temperature } T}{\text{Eddy-current loss at temperature } T_0} = \frac{234\cdot5 + T_0}{234\cdot5 + T}$$

where T = temperature to which the losses are to be corrected, and

T_0 = temperature at which the total losses are measured.

The losses in the magnetic shunts due to the leakage flux which they carry are inseparable from the total parasitic losses by any known test methods. In the above corrections they are assumed to vary as the eddy-current loss for copper. Any error due to this assumption is small owing to the low value of these losses, which can be approximately calculated.

MEASUREMENTS OF RESISTANCE.

The cold resistance measurements are taken when the transformer is in a complete state, i.e. when it is fully mounted and all permanent connections are made on both windings.

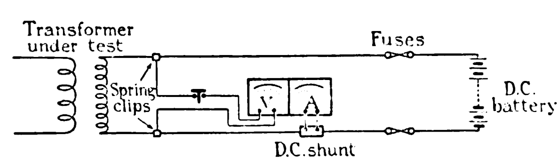


FIG. 17.—D.C. resistance measurement diagram.

An accurate measurement of temperature should be taken at the same time as the resistance, and special care should be observed to obtain the average value for the winding. Thermometers should be inserted between

the windings, in actual contact with the copper if possible. If the transformer is immersed in oil, the temperature of the latter is taken as that of the copper if the transformer has been immersed in the oil for six or seven hours at a steady temperature.

Several methods are in use for obtaining resistance measurements of the indirect or direct type. The direct methods include the use of such instruments as the ductor, Wheatstone bridge, Kelvin bridge, and standard balance. None of these methods are recommended for transformer-resistance measurements, as they are generally influenced by thermal and capacity effects.

The method recommended is the indirect one, using an ammeter, voltmeter and a d.c. battery as shown in Fig. 17. A precision ammeter and voltmeter should be used, perferably of the combined type with various ranges of shunts and resistances for the instrument, and the whole apparatus should be set aside for resistance measurements only. The voltmeter leads should be connected to the terminals of the transformer separately, so as to exclude the voltage-drop in the current leads where they are clipped to the terminals. A spring-release switch in the voltmeter circuit is essential for protection against induced voltages.

In measuring the resistance of transformer windings, it is very necessary to take care that all electrical circuits linked up by the same magnetic circuits are open-circuited before any readings are taken. If a d.c. supply is switched on to a transformer winding with the other winding short-circuited, a current is induced in the short-circuited winding which opposes the main current. This has a choking effect on the main current, causing it to rise very slowly, whilst at the same time the voltmeter reading is relatively high. This means that the magnetic circuit is damped and the flux, which has to rise to a maximum value before a steady reading can be obtained, rises very slowly, the whole system being in a state of change. Instances of this state of change having been maintained for a

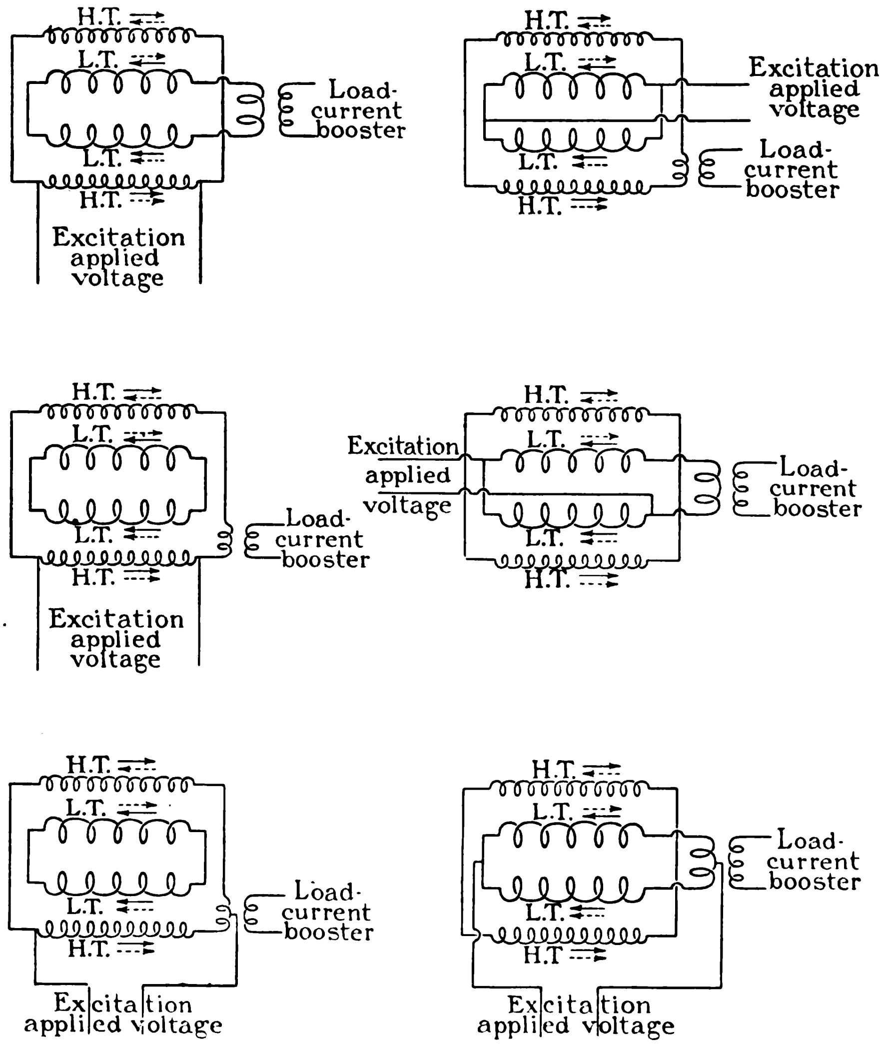


FIG. 18.—Full-load single-phase back-to-back connections.

period of 20 minutes after switching on are on record for heavy-current low-resistance windings. The d.c. supply voltage should be increased momentarily to a higher value than that intended for the readings, thus giving the circuit a dropping condition instead of a rising one.

As the circuit is very sensitive to slight changes in either the electrical or magnetic circuits, the use of a d.c. battery is essential if accurate readings are to be obtained, as the ripples or fluctuations in a d.c. supply are magnified by the coupling between the electrical circuits.

The resistances are usually measured on the particular tappings on which the temperature-runs are taken, as they will be the windings on which the hot resistances are measured.

Full-Load Temperature-Runs.

The load-run or temperature-run on a transformer is one of the most important tests to be carried out, for by this means only can the temperature-rise under full-load conditions be ascertained. The dead loading of transformers other than very small ones is out of the question, owing to the excessive cost, waste of power, extensive plant and high voltages which have at times to be catered for.

Load-runs in general are carried out on a test-bed in such a manner that the full-load losses are supplied without wasting useful power. There are many ways of approximating the load and losses, but those that are most nearly representative of true service conditions are here dealt with.

Single-phase transformers.—A single-phase transformer cannot in general be run on load by itself; it must either be run with a duplicate transformer or with one of larger size having the same ratio.

Approximate load-runs, so called, are often made on single transformers by either an overload short-circuit run or an over-excitation open-circuit run, the losses supplied in each case being equal to the total measured losses of the core and windings. These approximate runs give oil temperatures only and are liable to injure the core or windings by excessive local heating. Temperature-rises by resistance measurements are valueless under such conditions of loading.

The load-runs for single-phase transformers can be divided into two classes :—

(1) Unearthed windings.
(2) Earthed windings.

Unearthed windings are most common and are run as shown in Fig. 18 by connecting them back to back, or virtually in parallel. The core losses are supplied by exciting the two transformers in parallel, and the copper or load losses by injecting in the parallel link of either the h.t. or l.t. winding a current equal to the full-load current.

The most accurate method is to excite on one side and inject on the other side, i.e. if the excitation is supplied on the l.t. side the boosting or injected current should be on the h.t. side. If for reasons of voltage or supply considerations the excitation and boosting have to be supplied on the same winding, then one transformer will be slightly out of balance with the other for excitation, owing to the drop of voltage across the booster. To obviate this, the excitation supply should be connected to the middle point of the booster if this point is available. It is usual to supply the losses from two sources of supply, and for this reason it is essential that the frequencies be not the same, or hunting will take place due to the polarity of the excitation and booster being opposite. The excitation supply should be kept at the correct frequency, and the booster supply one or two periods higher or lower, the injected power being measured and adjusted to equal the winding or copper loss as measured.

For earthed transformers, which are usually for high-voltage service, the excitation and loading must necessarily be carried out on the l.t. side. This is due to the high voltage that would be present across the booster if loading were done on the h.t. side, for this voltage would be twice the impedance voltage of one transformer and would bring the earth point of at

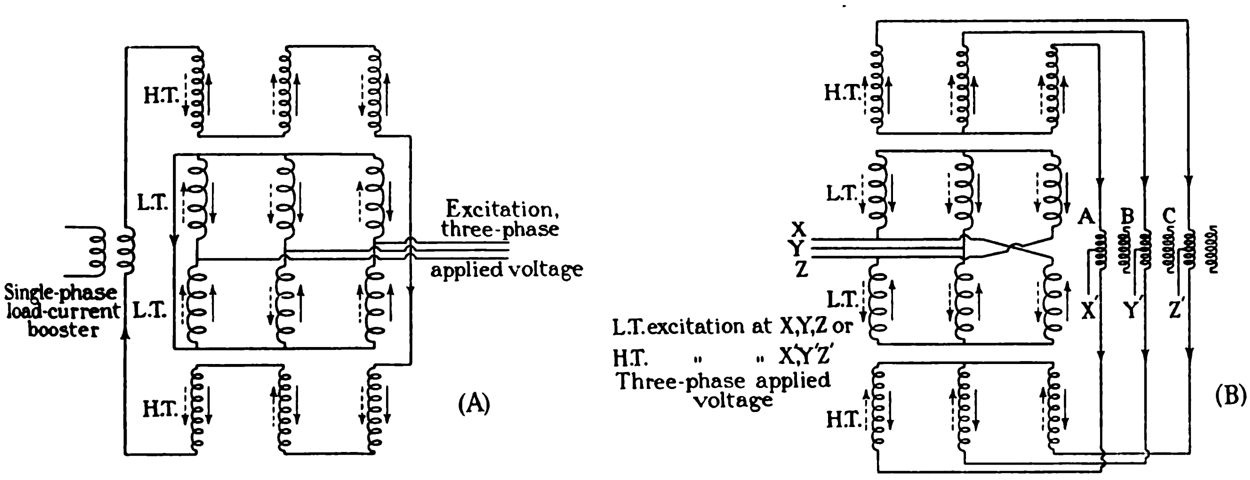


Fig. 19.—Full-load run diagram for three-phase star-star transformers back to back; single-phase or three-phase boost.

least one transformer to a possibly unsafe voltage above earth.

Three-phase transformers.—The loading of three-phase transformers is carried out in a similar manner to that of single-phase transformers, but due to the numerous methods of phase connection possible it presents a more difficult problem. The excitation is carried out by applying a three-phase voltage, and the load current injected is either single- or three-phase. With some forms of phase connection, as described later, three-phase injection of load currents is the only means possible.

Fig. 19 shows standard star/star transformers connected up for load-runs under alternative conditions. The method shown in A is one very commonly used, gives satisfactory results, and is simple to connect up, there being no necessity to phase out. This method entails the opening of the star connection and the re-connecting of the h.t. windings in series.

The advantages of this method are simplicity of connections, balanced conditions on the two transformers, service voltage conditions, and balanced loading of the two transformers. The disadvantages are: complex connections due to phasing out, a three-phase booster required, two three-phase supplies, and more losses in auxiliary apparatus. The method shown in A (Fig. 19) must on no account be used for delta transformers, i.e. a delta-wound transformer must never be temporarily connected in series or in Z-connection or undue stress will be put across the windings.

For transformers wound for delta/star connections the methods of loading shown in Fig. 20 (A and B) are most frequently used. In the method shown in A the high-tension or delta windings are left open and the two windings are connected in series through a booster. This method is not suitable for transformers of high reactance owing to excessive load losses, as described under copper-loss measurements. For transformers of this type the method shown in B must be used in order to give balanced service conditions.

The advantages of the method shown in B are similar to those described for star/star-wound transformers, and only one load-current ammeter and one three-phase supply required.

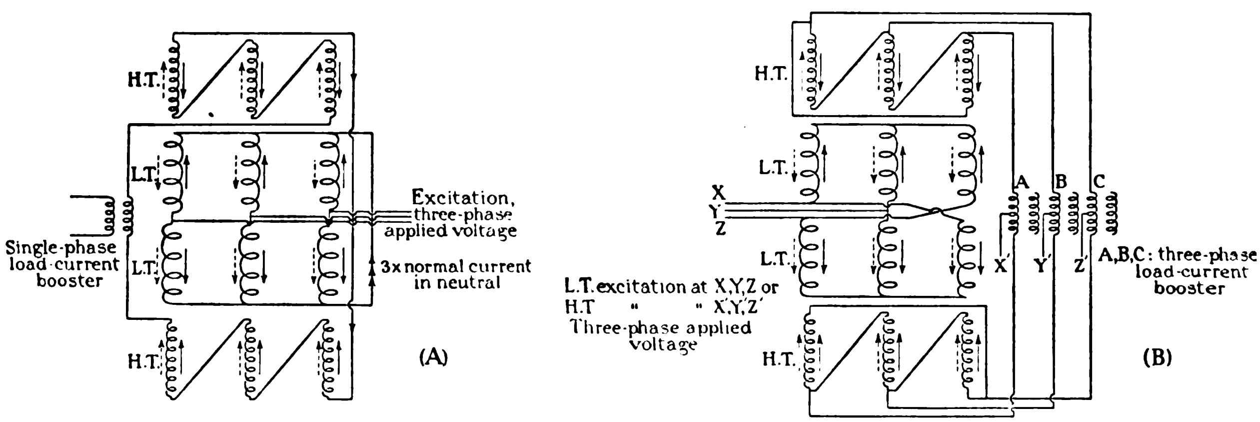


FIG. 20.—Full-load run diagram for three-phase delta-star transformers back to back; single-phase or three-phase boost.

The disadvantage is that, if the transformers have a high impedance, the voltage across the booster will be high, being approximately equal to the sum of the impedance voltage for the six legs of coils. There is also the disadvantage of temporary internal connections. This supply of the load loss by the series method does not give the true copper loss, as already explained under copper-loss measurements, and so the load current has to be adjusted to inject the equivalent of the true measured losses.

There are many variations of this method, such as exciting and boosting on the h.t. side, etc.

The method shown in B (Fig. 19) is not often used, but it is the most accurate method of loading giving balanced conditions throughout and voltage conditions exactly as in service. If in this method it is found necessary to excite the same windings as those into which the boost is introduced, the mid-points of the booster should be taken for the excitation, to maintain balanced conditions on the two transformers. The advantages of this method are: no temporary internal connections, service voltage conditions, and balanced loading of the two transformers, with the additional advantage that it can be used for such transformers if the h.t. winding is temporarily connected in delta. The disadvantages are the temporary internal connections and the necessity for strengthening the l.t. neutral temporarily to carry three times the normal current. This entails extra work and also adds slightly to the losses by those induced in the temporary neutral lead. The method shown in B has balanced conditions throughout and requires no temporary internal connections.

Star/interconnected-star transformer loading.—Transformers having interconnected-star windings are in a category of their own, the only possible means of fully loading being by the three-phase circulation method. This is due to the interconnections of the windings and the internal impedance set up on that account.

Fig. 21 shows the only scheme of connections possible for reliable results. Other methods such as unbalanced tappings rarely give full circulating-current conditions. The energy dissipated is difficult to measure accurately, and thus only approximate temperature-rise results can be obtained.

Extra-high-voltage transformers.—For transformers

wound for extra high voltage, i.e. for voltages above 33 000, star-connected and earthed or unearthed, the excitation and loading must be carried out on the l.t. side, as loading transformers are usually not available for such high pressures between windings and earth. For this type of transformer the scheme of con-

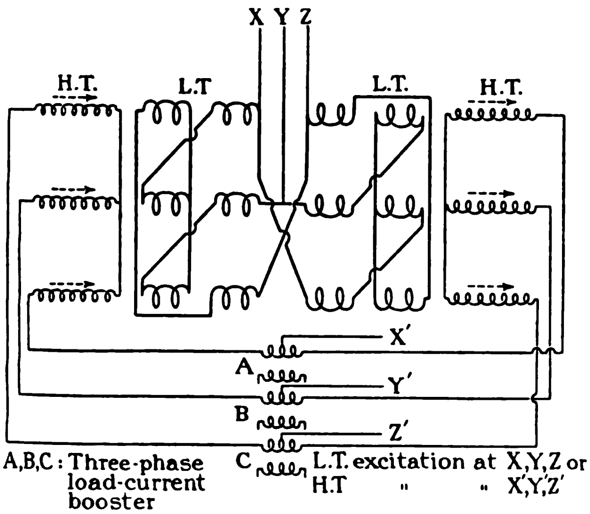


FIG. 21.—Full-load run diagram for three-phase star-interconnected-star transformers.

nections recommended is shown in Fig. 22. If the e.h.t. winding is delta-connected, then either of the two following methods may be used, and they are also applicable to any three-phase transformers of low impedance, so long as their windings are not inter-connected.

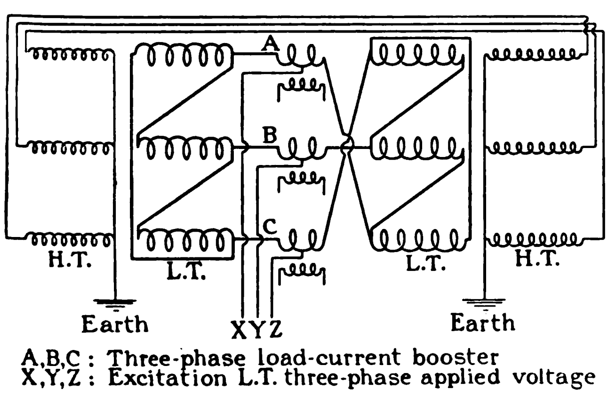


FIG. 22.—Full-load run diagram for star-delta transformers with high-tension earthed neutrals.

Fig. 23 (A and B) shows the connections, only one transformer being used. In A the booster is inserted in the h.t. delta and must be capable of withstanding the sum of the impedance voltages of the three phases to earth, for one side of the booster winding can be earthed. There is a disadvantage in this scheme apart from the slight out-of-balance of voltage in the phases, namely, that the terminals connected to the booster are not subjected to any severe potential strain during the temperature test. This is a serious disadvantage, for if the terminals be of the condenser type, for which the amount of internal heating should be tested during the run, they are not in their weakest condition when pressure tests have to be applied.

When transformers have to be connected temporarily in delta there is the common disadvantage that the stress or potential difference between phases is not equal to that under service conditions. In cases of this nature it is essential that the temporary connections be removed, the star formed and a three-phase over-potential test applied, to ensure soundness of insulation between phases and between primary and

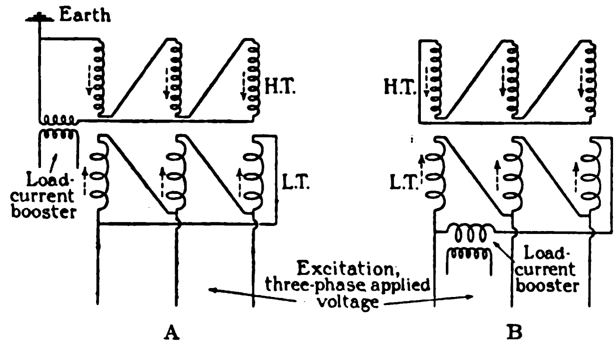


FIG. 23.—Full-load run diagrams for three-phase delta-delta connected transformers; high-tension or low-tension boost.

secondary windings. Fig. 23 (B) shows the same method with the booster inserted in the temporary delta on the l.t. side, thus leaving the e.h.t. windings free from any earth connections.

Whilst the above methods are suitable for a single transformer, it is advisable that if two are available a three-phase temperature test should be carried out as in Fig. 20 (B), but with the three-phase booster in the l.t. side and the excitation on the l.t. side applied to the mid-points of the booster.

Another method of loading is that of using two generator sets, one to supply and the other to load,

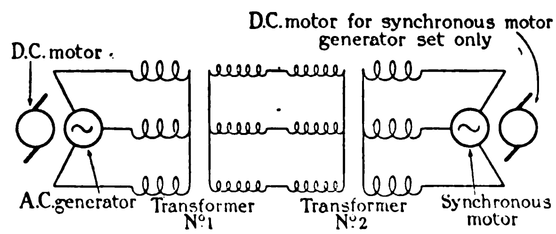


FIG. 24.—Back-to-back full-load run with a.c. generator and synchronous motor.

adjusting the excitation until full current is circulated in the transformers. One a.c. machine acts as a generator with the field adjusted to maintain full voltage on the windings, and the other as a synchronous motor under-excited to circulate the full kVA on the transformer windings at a low power factor. This method, shown in Fig. 24, gives a true heat test on one transformer only, as the voltage applied to the second transformer is reduced in proportion to the regulation of the first, causing a low iron loss on the

second transformer. It is usual to over-excite the one transformer by an amount equal to the reduction on the other, so obtaining an average figure for the heating.

The chief disadvantage of this method is the necessity for very large a.c. generators, at least equal to the kVA of the transformer under test, and also a very large range of voltage on the generator. One set consisting of three machines on the same shaft, i.e. two a.c. generators and one d.c. variable-speed motor, would be the ideal scheme for this method. The chief advantage of the method is that the transformer loading is all carried out at the same frequency.

The foregoing comprise the chief methods of transformer loading for shell-type as well as core-type transformers. The three-phase boosting method is that recommended by the authors, for the reasons that it gives a well-balanced and true loading and permits the transformers to be run without any temporary internal leads. They can thus be run in their completed condition with covers and all terminals in position, unless cable boxes are used instead of open-type terminals. The disadvantages are that more plant is required, and in each case it is essential that two transformers be available in order to carry out the test.

While from a customer's point of view the transformer should be run in a complete condition, this is, as already stated, often impossible due to the temporary leads required and the use of cable boxes which, for obvious reasons, cannot be connected up on a test-bed.

With every full-load run a full log should be kept. All readings required should be logged every half-hour and the temperature-rise characteristic plotted at the same time. The temperature of the oil should be obtained by means of distant-reading thermometers, in the interest of safety and to obviate the necessity for shutting down while such readings are taken. An ordinary mercury-bulb thermometer can be inserted in the oil as a check on the distant-reading thermometers, but this should only be read at the time of starting and shut-down. Air temperatures should be taken throughout the run and the air thermometer should be in a position free from draught and within 5 ft. or 6 ft. of the transformers. It is suggested that this air-reading thermometer be a mercury thermometer constantly immersed in a container of transformer oil at atmospheric temperature and pressure, thus eliminating the effect of rapid fluctuations of air temperature. These fluctuations, whilst they may give a true reading for the air at the instant, have little influence on a large transformer full of oil, hence, if recorded, errors in actual temperature-rise readings may easily occur.

The above readings are those required for oil-insulated self-cooled transformers. For other types, such as water-cooled, force-cooled, air-blast, etc., other records are necessary, and each and all must be taken with care and correctly logged. The temperature load-run should be carried on until the temperature-rise gradient is negligible.

Hot resistance measurements.—Immediately after the temperature test, the resistance must be measured and no time must be lost in obtaining this figure. The measurement is carried out in the same way as that already described for cold resistance measurements. The time from shut-down to the first measurement must be recorded, and for this purpose a stop-watch is recommended.

Several readings should be taken at half-minute intervals, the results plotted, and the curve traced back to the time of shut-down.

The correction for the resistance when hot at the time of shut-down, as given in the standard rules apart from extrapolating back to the time of shut-down, is based on the watts lost per lb. of copper in the transformer. If the loss does not exceed 7 watts per lb. 1 degree C. per minute is to be added to the temperature-rise calculated from the resistance, up to a maximum of 4 minutes. For higher losses per lb. up to 30 watts, the correction is the product of the loss per lb. and the following factors:—

1 minute, 0·19	3 minutes, 0·43
2 minutes, 0·32	4 minutes, 0·5

As a typical example of the similarity in results, the following test (see Table 6) is given, the temperature-rise being corrected by both methods.

The test was taken on a high-voltage transformer of 7 800 kVA rating, single-phase, 50 frequency.

TABLE 6.

Extrapolating-back Method.

Hot resistance after shut-down	Time after shut-down
1·872 ohms	3 minutes
1·869 ohms	3·5 minutes
1·863 ohms	4 minutes
1·858 ohms	4·5 minutes
1·858 ohms	5 minutes

Cold resistance at 32° C. = 1·76 ohms.

Extrapolating back to the point of shut-down gives 1·9 ohms, which with a cold resistance of 1·76 ohms gives an actual temperature of 53·5° C.

With an air temperature of 20° C. the temperature-rise is 33·5 degrees C.

Loss per lb. correction method.

The loss per lb. of h.t. winding = 11·75 watts at 75° C.

Time after shut-down = 3 minutes, and correction factor = 0·43.

The temperature-rise to be added to that after 3 minutes is thus:—

$$11\cdot75 \times 0\cdot43, \text{ or } 5 \text{ degrees C.}$$

The temperature-rise by resistance after 3 minutes, from the above resistance figures, is 28 degrees C. Thus the corrected temperature-rise is 33 degrees C.

The difference in the temperature-rises by the two methods is 0·5 degree C., a negligible figure. For accuracy and simplicity, it is recommended that the extrapolating back to shut-down be used whenever possible.

Transformers of different types having different methods of ventilation and cooling have, of necessity,

different cooling constants. Further, the methods employed when stopping a load run must be studied, or incorrect results will occur and cooling constants be affected. Self-cooled transformers are easily dealt with, but for artificially cooled units all means of cooling must be stopped at the instant of shut-down, and this in many instances is difficult. For instance, with air-blast transformers the fan takes time to come to rest, for water-cooled transformers it takes time to shut off the water supply, and for force-cooled units time is required for shutting down the pumps, i.e. oil and water circulation.

The methods employed for measuring resistance have already been described, but for hot resistance measurements it is necessary to have all instruments and leads ready for attaching to the transformer terminals as soon as the transformer is shut down. It is of advantage to have these leads fitted with spring clips.

The temperature-rise by resistance is calculated in the standard way where the resistance of copper is taken as proportional to the absolute temperature.

$$\frac{R_2}{R_1} = \frac{T_2 + 234 \cdot 5}{T_1 + 234 \cdot 5}$$

$$T_2 = \frac{R_2}{R_1}(T_1 + 234 \cdot 5) - 234 \cdot 5$$

$$T_2 - T_1 = \text{temperature-rise}$$

where R_2 = hot resistance at temperature T_2,
R_1 = cold resistance at temperature T_1,
T_2 = calculated final temperature, and
T_1 = initial temperature, both Centigrade.

The temperature-rise calculated from the increase in resistance does not give the maximum temperature of the transformer but the average temperature, and in some cases may give a result lower than the maximum oil temperature.

Insulation Tests.

Insulation tests should be taken with the insulation in its weakest condition, i.e. at the full-load temperature, so that these tests should follow immediately after the hot resistance measurements.

The insulation tests are as follows :—

(1) Over-potential tests.
(2) Pressure tests between the h.t. windings and the l.t. windings and core.
(3) Pressure tests between the l.t. windings and the core.

The above tests are those carried out on all double-wound transformers having h.t. windings fully insulated from the core and earth. If the h.t. windings have graded insulation, i.e. one end or the star point earthed, then test (2) is not possible and the test between the h.t. and l.t. windings is carried out at the same time as the over-potential test.

The value of the pressure and over-potential tests are stated in all standard rules, but at times customers depart from these standards, feeling that by increasing them they are securing a more robust and safe winding. This often gives a false sense of security. The order of the tests is usually that given above.

The over-potential test which tests the insulation between turns, layers, coils and phases, of a three-phase transformer is taken first while the insulation between the turns is in its weakest condition due to the effect of the expansion of the copper. With three-phase transformers it is advisable to apply the over-potential by means of a three-phase voltage and thus ensure a full test between phases ; incidentally it saves a considerable amount of time.

If the over-potential test is applied single-phase to each phase in turn, the stress between phases is not that to which they should be subjected, being only about 90 per cent of that required.

The over-potential test is usually at twice the normal voltage, and this is applied to the l.t. windings at a frequency approximately equal to, or higher than,

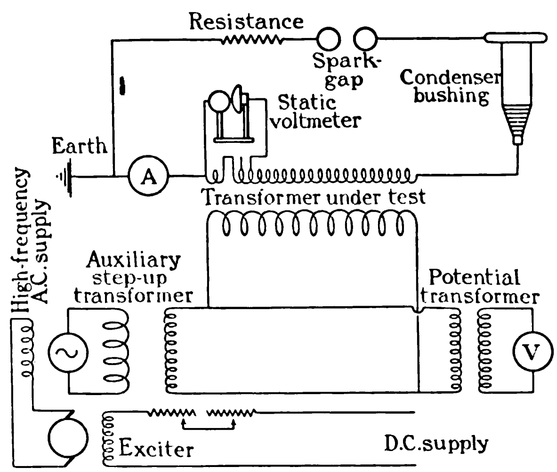


FIG. 25.—Over-potential test layout diagram.

twice the normal frequency. This is essential in order to keep the excitation of the core within saturation limits and the magnetizing current at a reasonable value.

The method adopted for the measurement of the induced voltage depends to a great extent on the type and line voltage of the transformer under test, or, in other words, it depends on the capacity of the windings to one another and of the h.t. windings to earth.

In general, for pressure tests up to 41 000 volts and over-potential tests up to 40 000 volts, i.e. for transformers rated up to 20 000 volts, the h.t. test pressure can with safety be taken from the transformer ratio of the testing transformer and the transformer under test respectively. For higher voltages the h.t. pressure must be measured by other means, due to the increase of voltage brought about by the capacity of the windings. This will be appreciated when it is mentioned that pressure-rises of 35 per cent above ratio voltages have been measured when testing transformers for 115 000 and 136 000 volts.

All insulation tests are given in R.M.S. values, assuming a sine wave of voltage, but the actual stress on the insulation is proportional to the maximum

value of the voltage wave. This value for a sine wave is R.M.S. × √2, but the effect of capacity in the circuit is to increase the second factor, and so the maximum value increases out of proportion to the R.M.S. voltage. Any instrument arranged to function on R.M.S. values of voltage will therefore give low and inaccurate readings.

The means of measurement are limited to spark-gaps and wave-crest voltmeters; the latter instrument is described later. Static voltmeters for very high voltages have not been found satisfactory owing to their delicate adjustment and susceptibility to vibration and draught, as they are usually dependent on the effect of a static field on a delicate diaphragm.

For over-potential testing, the spark-gap is recommended as the most reliable means of measurement, the calibration being that given in the Standardization Rules of the American Institute, with corrections for barometric pressure and temperature.

Fig. 25 shows a scheme of connections for an over-potential test on a high-voltage transformer, and is self-explanatory, but some notes may be of interest. Connected across the h.t. windings (in the case under review the h.t. terminal and earth), is a spark-gap with the correct size of spheres, and between the gap and earth is a high ohmic resistance of a value equal to approximately 1 ohm per volt of the test voltage. The best resistance is a column of water, preferably running water, so that a constant resistance is maintained. The absence of resistance in series with the gap is not advisable owing to the severe strain put on the windings when the gap flashes over. The tappings on the h.t. windings are bridged with a static voltmeter as an indicator. Inserted between earth and the earth end of the winding is an ammeter which gives the capacity current to earth and so is of service in determining the capacity of the windings to earth if the frequency is known. Across the l.t. side of the transformer under test is a voltmeter or a potential transformer, and a voltmeter is across the secondary side.

The gap is set to the required voltage and the high-frequency alternator runs up to the lowest frequency at which it is estimated that the required voltage can be obtained. The alternator is then excited with a weak field and this is gradually increased in strength until the gap flashes over. At this point the voltmeter reading is noted and the supply cut off. When the transformer is dead, the spark-gap is disconnected from the terminals and the voltage raised to the same value as that previously recorded on the voltmeter. The voltage across the h.t. side of the transformer will be that at which the gap sparked over, and the static voltmeter confirms this by giving the same reading as previously. The test voltage is maintained for the required period and then gradually reduced to zero and the supply cut off. While this test is being carried out a critical examination should be made of the transformer, and the instruments in circuit should be watched for fluctuations. If the oil is visible it should be closely watched for bubbles, which may burst into puffs of smoke, indicating creepage. Should a violent disturbance occur, it points to a flash-over. If the disturbance be accompanied by large volumes of smoke, then it is fairly certain that a breakdown has occurred which must be located later. Should any of the foregoing defects arise, the actual point on the oil surface will give some guide as to the region in which the failure has occurred. In many instances the oil is not visible, and in these cases the transformer must be carefully listened to by contact with the tank, and the instruments must be closely watched. Variations of hum or any crackling sounds, etc., should be noted.

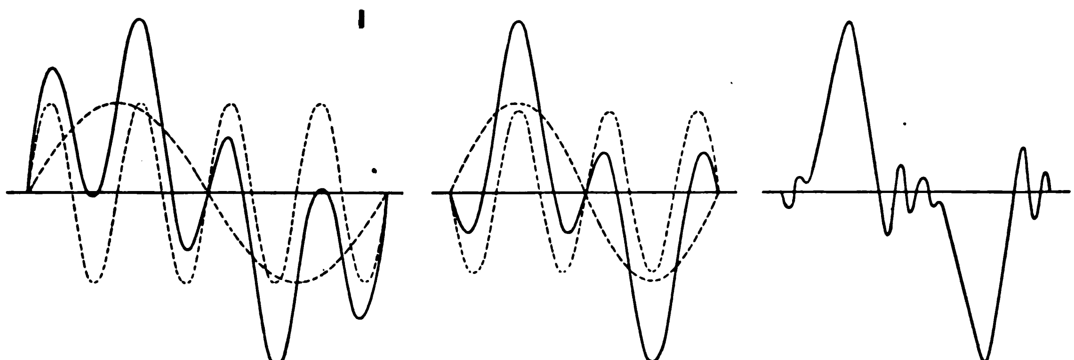


FIG. 26.—Superimposed waves.

If a failure occurs and the machine is automatically disconnected, the test should be repeated, and if the voltage can again be maintained the fault may be put down to a flash-over, which has probably occurred across the oil from the nearest point to earth or possibly between adjacent leads and tappings. Air bubbles are also liable to cause flash-overs, but ionization quickly disperses them.

If the voltage gradually falls with repeated tests, the fault is almost certain to be due to creepage across the insulation, which is thus being gradually weakened. If the voltage can be maintained only at a low value the fault is then certain to be a dead earth or a short-circuited turn or turns in the winding.

When abnormal tests are required, such as three or four times the normal voltage, a high frequency is necessary to obtain this test value. With high-voltage transformers very high frequencies are apt to bring

about complicated conditions and troubles. These high-frequency tests set up intense static fields and discharges under oil, causing flash-overs and disruption. Several instances of such trouble are on record, and it is recommended that a frequency not greater than 175 be used for high-voltage testing and over-potential testing.

Where abnormal tests are required necessitating a higher frequency than 175 periods, the authors have devised other means of obtaining the voltage without creating disturbing conditions. The method used involves two sources of supply, one at a high frequency, say 200, and another at 50 or 66·6 periods, and the superimposition of one supply upon the other. The resultant wave is a distorted one, but the period of maximum voltage is not less than the lower frequency of supply. To obtain the best condition the higher frequency should be a multiple of the lower frequency, thus giving a regular peak voltage.

Typical examples of superimposed waves are shown in Fig. 26. These curves show theoretical superimposed waves of ratios 4/1 and 3/1, and also a reproduction of an actual wave taken during a test under these conditions with a frequency ratio of 3/1.

Pressure Test.

If the transformer has unearthed windings, then a pressure test to the core or earth is required and is carried out by the application of a high pressure between the h.t. winding and earth, the l.t. winding being earthed during the test. The high pressure must be applied to both terminals of the h.t. winding being tested, and also to the tappings should there be any, so as to preclude any pressure-drop through the windings, which might occur if it were only applied at one point.

The test pressure should be obtained from a testing transformer of ample kVA capacity to deliver the full test pressure and energy required without strain or drop in voltage, and the frequency of supply should not be lower than that for which the transformer under test is designed.

The test pressure should be measured in a manner similar to that described under over-potential tests, i.e. by a spark-gap or a crest voltmeter.

Crest voltmeter.—This functions on the principle that the average charge current of a condenser is proportional to the maximum impressed voltage. To obtain the average value of the charge current it is necessary to rectify the alternating current and measure its value on a d.c. milliammeter.

In order to use the crest voltmeter the testing transformer must be fitted with a condenser bushing or a fixed standard condenser. The condenser bushing is generally used, the earth band of the bushing being insulated from the tank and the charge current passed through thermionic valves or mercury rectifiers to earth. The rectified current is measured by a d.c. moving-coil permanent-magnet milliammeter.

Two circuits which give satisfactory results are given in Figs. 27 and 28, which show the full-wave and the half-wave rectification respectively. The full-wave rectification method is to be preferred, as the current measured is approximately twice that of the half-wave rectification, depending on the total impedance of the valves and condenser circuit. The filaments of the valves must be heated by separate supplies, except where the two valve filaments are connected. Thus for full-wave rectification three separate sources of supply for filament heating are required, and two sources for the half-wave rectification. Accumulators are satisfactory where small rectifying valves are used, but it will be found more convenient and satisfactory to heat the filament from a transformer with the

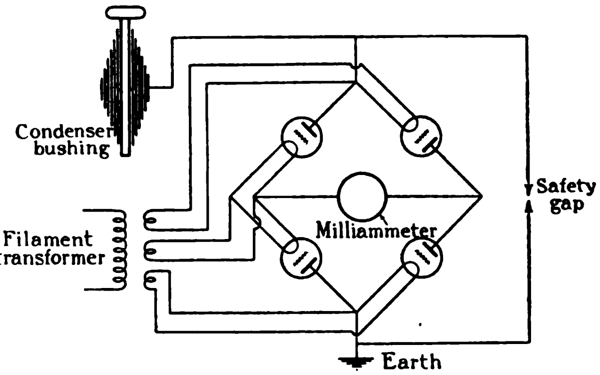


Fig. 27.—Four-valve crest voltmeter.

required separate l.t. windings. A very small pointed spark-gap is shown in the diagram across the condenser and the earth terminal. This is to take the main charge current when a heavy current passes through the terminal bushing condenser, which would otherwise spark across between the plate and filament of the valves and probably burn them out. Sparks pass across this gap at every breakdown of the h.t. circuit of the testing transformer, and therefore provide a good indication of a breakdown as well as functioning as a safety device.

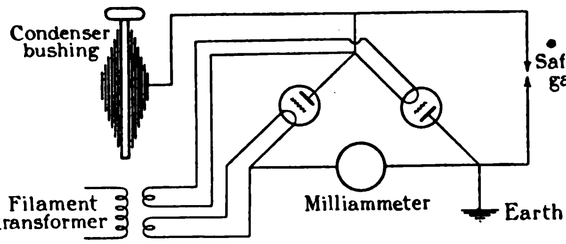


Fig. 28.—Two-valve crest voltmeter.

The charging current of a condenser being proportional to the frequency, capacity and voltage, it is very important that the frequency should be kept constant during calibration and when using the above method.

A zero error will be noticed when using either of the circuits, but this can be allowed for if necessary. It is caused by the emission of electrons from the filament to the plate sufficient to reduce it to a negative value lower than the filament and is called the space charge. When using the two-valve circuit this can be compensated for by inserting in the earth lead a

number of cells sufficient to reduce the plate voltage to a negative value low enough to stop the emission, but no very great advantage results from its use, except in connection with very low readings.

The possible errors and disadvantages of the crest voltmeter may be briefly summed up as those due to change in frequency of the charging current, and apparent change in the condenser capacity due to corona stresses and to the rectification characteristics of the valves. If the crest voltmeter is checked periodically by means of the spark-gap no trouble should be experienced.

The grids of the valves are left insulated as shown in the diagram, but if the voltage across the valve is sufficiently low they can be connected to either the filament or plate circuit.

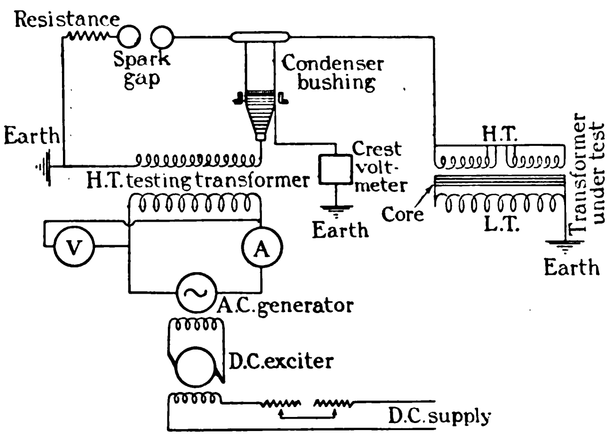


FIG. 29.—Pressure-test layout diagram.

In connection with the pressure testing of transformers, the testing transformer should be fed preferably from a variable-speed alternator, to give the desired frequency, with its field excited from an exciter on the same shaft, itself excited from an independent and constant supply such as a battery. This requirement is to ensure as far as possible a constant voltage.

The arrangement of the test is shown in Fig. 29 and the procedure is similar to that already described for over-potential testing. With this type of test the spark-gap is used as a measure of test voltage, and the crest voltmeter as an indication that the voltage has been reached when the gap is disconnected. A voltmeter is also used across the l.t. windings of the testing transformer calibrated in h.t. volts, and the reading recorded on this meter gives, when compared with the test voltage, a measure of the increase in voltage due to the capacity of the transformer under test. An ammeter inserted in the l.t. winding of the testing transformer will give a measure of the load, and any fluctuation in the reading during the test will give an indication of creepage. It is recommended that before the testing transformer is connected to the transformer under test the crest voltmeter be calibrated with the spark-gap for each test voltage required, and that during the test the spark-gap be cut out, thus eliminating possible surges due to the breakdown of the gap.

STANDARD REFERENCES.

In connection with all tests, such as those for losses and temperature, the results obtained should be corrected to certain standard references and basic values set up by the various Standards Committees, so that true comparison can, if necessary, be made.

These references cover wave-form, temperature, barometric pressure, etc., and are clearly stated in all standard rules, so that they need not be detailed here.

TRANSFORMER OIL.

All oil used for transformers should meet the required specifications, but of these only the question of moisture and breakdown value really affect the testing of transformers. All oil used must be dry and have a high breakdown value and must be clean.

Oil may be dried and cleaned in many ways, but the quickest and most efficient method is by the centrifugal oil separator, of which several different makes are on the market.

The oil in which transformers are tested should have a breakdown value of not less than 30 000 volts across a standard gap of 0·15 inch with 0·5-inch spheres.

The test for breakdown should be carried out at 50 periods, for the breakdown value falls slightly at high frequencies. The temperature at which the test is taken is not very important, as temperature has little, if any, effect over a wide range and is said by some to increase the dielectric value slightly up to 65° to 70° C.

CONCLUSION.

The authors have covered, in the foregoing, the main tests carried out every day in connection with transformers, and have endeavoured to point out the best means, to their knowledge, of obtaining the most accurate commercial test-results, the type of apparatus to use and its possible errors and accuracy.

There are many other tests in connection with transformers, such as surge tests, short-circuit tests, dielectric tests, etc., but as these are special and not general they have not been dealt with, as each would provide a subject on which an interesting paper could be written.

In conclusion the authors would like to express their thanks to the Metropolitan-Vickers Electrical Co., Ltd.

DISCUSSION BEFORE THE INSTITUTION, 21 JANUARY, 1926.

Mr. S. A. Stigant: I cannot too strongly endorse the authors' views with regard to the importance of tests which will give undoubted and undeniably accurate results, because, as the authors have said, such tests create a very strong feeling of confidence in the minds of users, and this is most important. At the same time I do not think that the apparatus to be used should be unnecessarily elaborate, and I consider that the authors have shown that modern transformer-testing practice is such as to remove any impression of that kind that a user or an inspector might have on visiting a maker's works. The authors refer to the use of the vacuum method for drying out transformers, and in very large works, where the special plant necessary for this method is available, I think it is probably the best method; but it is quite possible to dry out transformers, even for the highest voltages, without having to resort to the vacuum method, and transformers for 250 000 volts have been successfully dried out in that way by the Company with which I am associated. The authors also refer to the necessity for the use of low-power-factor wattmeters in the iron and copper loss tests. The majority of manufacturers have found that that is a really vital necessity, because very considerable errors are introduced into loss readings by the use of the ordinary commercial wattmeters that are really designed to operate on higher power factors. In connection with the measurement of iron losses, the testing facilities may not always be available for applying to the windings the voltage for which they are designed, and it is well to bear in mind (I am addressing my remarks now particularly to the makers of transformers) that the iron-loss test can be conducted equally well if the windings are fitted with a tapping which will give a voltage corresponding to that of the machinery which is available. That is to say, all that one has to do is to maintain the normal flux density in the core. Certainly one would usually get a higher magnetizing current, but the magnetizing ampere-turns would be the same. In their notes on heat runs the authors say that when testing three-phase transformers the copper losses should not be tested single phase because they give inaccurate readings, and further on they refer to a series and Z connection for the three phases. In those conditions, I agree, no single-phase test should be given, but it is quite permissible to test each limb single phase, i.e. apply a pressure to the winding on one limb, short-circuit the other winding on the same limb and have the windings on the other limbs all open-circuited. This method gives results practically identical with those of the various three-phase tests cited by the authors. This question of losses and heat runs is a very vital one, and is of particular importance in the case of large transformers. I should like to bring to the notice of the authors the use of static condensers to reduce the kVA of the testing plant required. If the condensers are shunted across the transformers the machines required for the heat runs or for the tests can be considerably smaller than when condensers are not used. Incidentally, if a public supply is used the power factor is improved, and it may be that the consumer can get better terms on that account. I am rather disappointed that the tests have not been illustrated by vector diagrams—diagrams showing the precise conditions which obtained under these different tests—because I know from actual experience, both with my own colleagues and in teaching junior students, that such diagrams are of very considerable use in explaining the precise cycle of events under these conditions. The authors refer to the rise in voltage which takes place when testing high-voltage transformers, and they say this is due to capacity current; this rise is of course due to the passage of the capacity current over the impedance of the transformer. That is the usual well-known phenomenon that occurs also when high-reactance rotary transformers are used for d.c. pressure regulation. It occurred to me when reading the paper, however, that the statement may be misinterpreted, and I should like to point out that the pressure-rise is due to a combination of voltage and current rather than to electrostatic capacity as such. We know that the three are bound up together, but it should be remembered that the electrostatic capacity of the different parts of a high-voltage transformer is generally considerably lower than that of transformers of much lower voltages. With regard to the question of the measurement of temperature-rise, it is also worthy of note that whilst the temperature-rise measurements by resistance give a closer idea of the maximum temperature inside the winding, we may get cases where the temperature-rise by resistance is only 1 deg. or 2 deg. more than that measured by a thermometer in oil, or it may even be lower. I believe that the authors have met these cases, and I should have liked to see a reference to them in the paper. In conclusion I think it is highly essential—and in this I am sure all makers and users of transformers will agree with me—that transformers should be tested, wherever possible, as nearly as possible under their actual service conditions. This particularly applies to the losses and the pressure test, where the supply should be at the rated frequency of the transformer.

Mr. S. W. Melsom: Dealing in the first place with the tests of insulation resistance, the authors use a megger, which is, of course, quite a good workshop instrument, although not necessarily capable of the highest type of accuracy for high values of insulation resistance. They refer to applying the voltage for at least 60 seconds. I think that Mr. Evershed in his paper laid stress on the need for applying the pressure for considerably longer than 60 seconds in most cases, and particularly with materials such as are used in transformers. A little further on in the paper the authors say that when the transformer is immersed in oil its megger reading will be much lower than that in air. It seems to me that the leakage current can only take its path through the oil, which presumably has a very high value of insulation resistance. I should like to know whether the fall of insulation resistance when the transformer is immersed is immediate or whether it only occurs after a time, i.e. whether the moisture

which is left in the insulation slowly diffuses into the oil. When discussing a workshop method of measuring copper resistance, the authors say that they have considered such methods as the Wheatstone bridge and the Kelvin bridge, but do not recommend them as they are generally influenced by thermal and capacity effects. I should like to point out, however, that although they have laid emphasis on the need for accuracy, yet they go on to measure the resistance of the copper by the ammeter-voltmeter method, and from that measurement determine the temperature-rise of the windings. The highest accuracy is required here, but the authors hark back to the very oldest known method of measuring resistance. They dismiss the other methods by saying these are influenced by thermal and capacity effects, but they do not explain what those thermal and capacity effects are. To my mind the method they use for determining the temperature-rise is roughly equivalent to that of determining the density of a metal by means of an ordinary spring balance. I am surprised that, when they really do need accuracy, they ignore the much more accurate and convenient method of the Kelvin double bridge. I have had considerable experience both of those and of various other types of apparatus for the measurement of resistance, and I cannot see anything special in a transformer which would induce thermal and capacity effects into the Kelvin bridge. On page 522 the authors suggest that the first reading of resistance is obtained 3 minutes after shutting down, and readings have to be taken up to 5 minutes to allow of extrapolation to the point where switching-off occurred. It is probable that the greater part of this 3 minutes is taken up in dealing with the arrangement (referred to later in the paper) of leads fitted with spring clips which are attached when the transformer is shut down. That method seems to me to be capable of improvement. It would seem that in a works, where switches are available, it should be possible to have proper switching arrangements such as I have used when making similar determinations with high-pressure cables. With proper switching and a Kelvin bridge for measuring, good readings could be obtained within 30 seconds of shutting down. I think the Kelvin bridge is condemned by most workshop people because it is an arrangement of resistances inside a box, but so far as a workshop method is concerned the time to obtain an accurate reading is less than with an ordinary ammeter or voltmeter, the bridge is much more accurate, and only one man, instead of two, is needed to operate it. Also it is portable. Perhaps the authors have found in the double bridge sources of error that have not hitherto been suspected; if so, I hope that they will explain these more fully.

Mr. A. F. W. Richards: On page 505 the authors say that accurate results are essential to create confidence in the mind of the customer, and with this remark I am in entire agreement. The information contained under the heading "Drying-Out and Insulation Resistance," if carefully observed, would largely reduce breakdowns on pressure and overpotential tests which frequently occur and certainly do not tend to create confidence in the customer. With regard to ratio testing, there are, as the authors point out, many inaccuracies which occur with both the voltmeter method and the standard transformer-ratio method, but I think that up to about a year ago only one manufacturer provided a resistance balance ratiometer, and even now I only know of two who have them. Iron loss is, as the authors say, very important. A very great deal depends on the use of proper instruments for the purpose of this test. The authors point out in Table 1 that the no-load current varies appreciably in each phase, but, unless it is specifically asked for, the current in all three phases is very rarely given in the test certificates. I think that that information should invariably be given. The more important point, so far as iron loss is concerned, is correction for form factor. One of my clients especially asks that an iron-loss voltmeter be used, or that sufficient information be given to enable the ratio to be deduced for an average value. I think I am right in saying that there is not a single test-bed in this country with an iron-loss voltmeter. What is generally provided to enable us to determine the form factor is an oscillograph record stated to be taken from the machine used for the purpose; but there is usually very little to give us real confidence that the oscillograph is a true record at the time of testing. The arrangement shown by the authors in Fig. 3 is very ingenious, and I hope it will become a commercial article. Under the heading "Separation of Losses" the authors give two examples which they used, apparently, for proving their own instruments. One gives a 30 per cent error with a form factor of 1·4, and the other 25 per cent with a form factor of 1·25. I should like to ask the authors whether those were artificial form factors or whether they are what we may expect when testing transformers and getting results which we send to our clients abroad. One would think that the measurement of resistance was the easiest test of all, yet in practice it gives more trouble than any other. Mr. Melsom has already referred to the subject and I hope this matter will be dealt with more satisfactorily by the manufacturers. As far as I am aware, there is only one test-bed on which fixed instruments with proper leads are provided for this test, and where the instruments are kept solely for this purpose. For load temperature-runs the authors give some very interesting diagrams of usual methods, but they have not given a very common form—using the voltage taps on the two transformers, putting the ratios slightly out of balance and so getting a circulating current. With regard to temperature results on small transformers, I think some warning should be given about the position of the thermometer. This may greatly affect the results. The authors give the American Institute Rules for determining the temperature at the moment of shutting down, and I am very interested in their remarks showing the close agreement between the extrapolation and losses-per-pound methods. When testing two transformers back to back one usually wants to take readings on both, and one has not time to extrapolate back. I am surprised that the authors do not mention the hot-spot method. I know the errors that are liable to creep in and the difficulty there is in getting the couples in the right place, but I think manufacturers' designers could help us if they were to try; and it is undoubtedly the most satisfactory method of measuring temperature-

rise. In conclusion, I should like to say that I know of cases where orders have been placed abroad solely because the purchaser was not satisfied that the methods of testing in use in this country would give him all the information he required. I hope, therefore, that manufacturers will benefit by this paper and improve their methods.

Mr. J. Bloome: The title of the paper suggests the testing of transformers irrespective of size, but the authors have dealt chiefly with large transformers which we are not at present accustomed to test every day. Fig. 2 gives a typical drying-out characteristic of a large high-voltage transformer under the vacuum process. I have at various times obtained similar characteristic curves on smaller transformers. In passing, I should like to mention a point of some interest. Two similar transformers were dried out, one by the circulation of dry air as described by the authors, and the other by heating up the transformer and supplying a current to the high-tension winding with the low-tension side short-circuited. I found that the shape of the curve was similar, the difference being that the time taken to go through the process was much shorter in the latter case. I cannot give any reasonable explanation of this; possibly it may be due to more localized heating. I should like to hear the authors' opinion. It would be of interest if they would indicate how the empirical formula on page 506 was obtained. With regard to the measurement of iron loss, I can substantiate the authors' statement that low-power-factor wattmeters are absolutely essential. Table 1 gives a comparison of readings obtained by the 2-wattmeter and 3-wattmeter methods respectively. The authors give this table to illustrate the variation of the power factor, and not really for a comparison of the watts, but I generally find when testing two similar transformers, one by the 2-wattmeter method and the other by the 3-wattmeter method, that there is a big difference in the readings. For high-voltage iron-loss testing the authors recommend the elimination of the current transformer and the earthing of the current coil of the wattmeter. Personally, I have experienced some serious discrepancies when measuring in this manner. This may possibly be due to some electrostatic action in the wattmeter. I have used a low-power-factor wattmeter in connection with calibrated current transformers and correction curves supplied by the instrument makers. I find these instruments quite accurate, and all that requires earthing is the secondary side of the current and potential transformers; complications are thus avoided. Having used both methods, for simplicity, accuracy and safety I prefer the latter. The arrangement for measuring frequencies described in the paper is very good, but I think the authors will agree with me that a well-designed tachometer used carefully and frequently calibrated is all that is required. The form factor plays an important part in the measurement of iron losses and is well worth the attention which the authors have given it. The examples given illustrate the errors that can occur due to bad form factors. I notice that in the first example of a large 25-cycle transformer the form factor is extremely bad, viz. 1·25. Was this due to the design of the transformer or to the method of testing? The authors recommend the three-phase measurement of copper loss with a three-phase transformer, but the copper loss can be measured single phase by short-circuiting each limb separately. With regard to resistance (by which I refer chiefly to the resistance for determining the temperature-rise) the authors recommend the use of a voltmeter and ammeter, but I find that an ohmmeter is more accurate. In addition, the visual error is minimized, since only one reading is taken instead of two. Also the ohmmeter is sufficiently robust to withstand heavy surges. I always recommend that the instrument be not moved between the hot and cold measurements of resistance. There is then no possibility of an error being introduced owing to the mishandling of the instrument, or anything of that kind. I can generally get the hot resistance in less than 3 minutes; I think that compares well with the time taken with a d.c. voltmeter and ammeter set. The authors must be complimented on their unique method of carrying out abnormal over-potential tests, which customers sometimes require, without increasing the dielectric hysteresis to a dangerous value. The authors recommend the use of a motor-generator set for the regulation of the voltage for pressure-testing. For this purpose I have used a motor-generator and an induction regulator, and I personally prefer the latter. This is easy to control; it does not require the same skilful attention as the motor-generator set, and if it is fitted with a well-designed compensating winding, and the iron circuit of the regulator is such that it will allow for small magnetizing currents on the lowest possible frequency likely to be used in testing transformers—25 cycles—everything is quite satisfactory. Further, one big advantage of the induction regulator is that it generally has a reactance of about 10 per cent which, when the transformer is put under short-circuit conditions due to flash-over or breakdown, will be a great protection for the testing transformer. Although the testing transformers are generally supplied with an air-core reactance used on the high-tension side, I have never found these to offer real protection. The induction regulator certainly does.

Prof. J. T. MacGregor-Morris: I particularly want to refer to the crest voltmeter described on page 513.

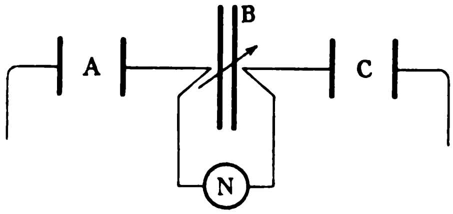


Fig. A.

I think it would be of material assistance to others who are using or intend to use this apparatus if the authors would give some values of the actual capacities of the bush when it is used and the value of the current, at some particular voltage and frequency, that flows through the milliammeter. The authors point out that this crest voltmeter depends on the frequency. A crest voltmeter has been developed by Mr. Ryall working in

my laboratories at East London College (and apparently simultaneously by Mr. Palm, of Hartman and Braun) which is independent of frequency. The arrangement is shown in Fig. A. Two high-voltage condensers, A and C, of small capacity, are connected in series with a variable condenser B of much greater capacity. Across the terminals of condenser B is connected a "beehive" neon lamp N. The capacity B is gradually decreased until the neon lamp glows. Then from the values of the capacities of A, B and C and the striking voltage of the lamp, the overall crest voltage is at once obtained. If certain precautions, well known to those who have worked carefully with such apparatus, are taken with the neon lamp, the striking voltage can be relied upon to, I believe, $\frac{1}{2}$ of 1 per cent. We have used it with entirely satisfactory results up to a pressure of 15 000 volts, and Mr. Ryall is continuing experiments in my laboratory which we hope will enable us to go very much further by the introduction of quite simple additions. I think that it is worth experimenting with, because the apparatus is simple and there does not appear to me to be any serious limitation in the voltage which can be measured by it.

Mr. F. S. Robertson: The valves used in the 2-valve crest voltmeter described appear to be 3-electrode valves, but the grids do not appear to be connected to anything. The object of using 3-electrode valves for this purpose is not apparent unless it is desired to make use of the grids by giving them sufficient negative bias to stop the circulating current which is the cause of the zero error observed by the authors. The circulating current is caused by the fact that some of the electrons are emitted from the filament with such large velocities that they can pass right across to the plate even against a considerable retarding potential. If a grid having a fairly close mesh is placed between the filament and the plate and is well insulated, some of these high-velocity electrons will strike it and in consequence may soon charge it to such a high negative potential that it is able to turn back the high-velocity electrons which were formerly passing through its meshes to the plate, and in this way shut down the main current through the tube. If the grid has a more open mesh, as appears to have been the case in the authors' experiments, a certain amount of current will pass and give rise to the zero error. It would seem to be a very great disadvantage to the method to have an insulated grid taking up an indefinite and unknown potential, seeing that the grid and its potential are controlling factors in the operation of the tube. Whatever type of tubes are used, one at least might have a grid with a negative bias on it sufficient to stop the zero error on the milliammeter. This could best be done by employing a cell or cells with the negative pole connected to the grid and the positive to the filament, or in the case of a close grid a high resistance between the grid and the filament, forming a grid leak, might be used.

Mr. F. E. J. Ockenden: Under the heading "Ratio Testing" the authors deal with methods of checking the ratio error of transformers, and they say "The procedure is so to adjust the dial switches as to obtain a true balance and a zero reading on the meter." In so far as the primary and secondary voltages have certain phase displacements, I do not see how an absolutely zero reading can be obtained on the wattmeter. It is doubtless possible to get a minimum reading, but that is unsatisfactory compared with a zero reading. The authors criticize the double-voltmeter method of ratio testing, but I have found a variation of this method to give very satisfactory results, avoiding the phase-angle troubles which are inherent in most wattmeter methods. In Fig. B, W_1 and W_2 are the transformer windings, R is a resistance, one end of which is subdivided as in a ratiometer, so that the ratio r/R may be continuously adjustable. V is a voltmeter, of either the electrostatic or high-resistance pattern. (In the latter case the value of its shunting effect across r must be allowed for.) K is a tapping key in series with W_2. The position of C is adjusted until, on depressing K, there is no change in the voltmeter reading when $W_1/W_2 = R/r$. This method of testing has the following advantages:—(1) The reading of the voltmeter V, when the key is closed, is influenced to

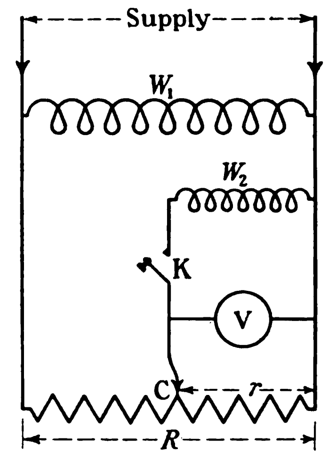


FIG. B.

an entirely negligible extent by the voltage-drop across r, the generated voltage in W_2 taking entire charge. Consequently, provided the voltages across W_2 and r are the same, no change will be caused in the reading of V, by difference of phase angle. Even when this angle is made 180° I have not been able to detect any error; the current consumed by R is of course small. (2) The voltmeter is easily arranged to read on the most open part of its scale, where small changes are easily detected; thus the lack of sensitivity of most a.c. instruments at the zero end is avoided. (3) Accurate calibration of the voltmeter is of no importance, since the same point on its scale is used for both the primary and secondary readings. Under the heading "Iron Loss and Magnetizing Current" the authors say that, to ensure accurate results, "For high-voltage iron-loss testing, provision has to be made for the insertion of potential transformers, but as the ammeter and current coil of the wattmeter are always earthed, no current transformers are necessary." They seem to think that this is an advantage, but I do not agree. The average phase angle of a really good voltage transformer is about 10′, and for an equally good current transformer

the figure is 12′ to 13′, both phase angles being in the same direction. This is an advantage in that the net phase-angle error introduced by the measuring devices is only 2′ or 3′ instead of at least 10′—an important consideration, in view of the extremely low power factor of all iron-loss measurements. Later in the paper the authors say that static voltmeters for very high voltages have not been found satisfactory, but I venture to think that they can have had no experience with the more modern instruments of this type. I know of a case where a 300 000-volt static voltmeter is successfully used in preference to a spark-gap, since, when both are checked against a high-resistance voltmeter of the most refined type, the accuracy of the electrostatic voltmeter is usually several per cent higher than that of the spark-gap however carefully the latter is manipulated. I consider that the so-called delicacy of the static voltmeter is very much exaggerated, great advances in the design of these instruments having been made in the course of the past few years.

Mr. H. M. Lacey: Under the heading "Three-Phase Core-Type Transformers" the authors give an explanation of a phenomenon which they describe as somewhat mystifying. It certainly is, and this is the first time I have seen any attempt at an explanation in print. Unfortunately, however, I find I cannot quite agree with that explanation. If the winding to which the pressure is applied is star-connected and the neutral is not connected to the neutral of the supply, then I think that the explanation may be right; but that phenomenon does occur even when the windings have their neutral point connected to the neutral point of the supply, and also in the case where the windings are delta-connected. In both these cases the voltage across the winding on each limb is definitely fixed by the supply, and therefore the flux in each limb also must be definitely fixed. I am not quite certain whether my views are correct, but I should be glad if the authors would add to what they have said in the paper on this matter.

Mr. H. S. Holbrook (*communicated*): I should like to support the author in emphasizing the desirability of making three-phase tests on three-phase transformers. Further, if one of the windings is normally delta-connected it is desirable that the delta be closed during tests, to duplicate as closely as possible the actual operating conditions. Similarly, should both windings normally be star connected, neither should be delta-connected during test. A more accurate method for full-load temperature-runs than any mentioned by the author, whilst still requiring a supply equal only to the sum of the losses, was suggested by me some years ago and tried out by the British Thomson-Houston Co. with success. Only one supply alternator is required. Current is circulated between the transformer under test and any other of convenient rating, and by means of a phase-shifter and an induction regulator, the applied voltage and the output current both in magnitude and in power factor are adjusted to the actual rated operating conditions. On some high-reactance designs, the operating conditions may make the question of power factor of great importance. The internal connections of the transformer under test are maintained as they would be in service. The alternative mentioned by the author of overload short-circuit is, as he indicates, a dangerous one to use on transformers with poorly ventilated windings, but on a modern transformer for use in a traction rotary-converter equipment guaranteed to withstand very heavy overloads it is quite a safe and good method. An approximation to the true temperature-rise of a winding under normal load current can be obtained by making in addition a short-circuit heat-run at rated current to determine the temperature-rise of the winding over the oil for rated current. The value thus obtained will be somewhat too great, as the actual oil temperature being lower than in normal operation, the oil viscosity will be greater than normal.

[The authors' reply to this discussion will be found on page 541.]

Western Centre, at Bristol, 1 February, 1926.

Mr. C. T. Allan: Can the authors recommend reliable, rough tests to find where a transformer is defective after it has broken down in service, when its weight and position may make it difficult and expensive to remove it to a test room, assuming that an ammeter, voltmeter, water resistance and megger are available, because sometimes it is found that a transformer may be repaired on site? Can they also indicate what are the worst conditions for producing oil sludge in a transformer? I am of opinion that the larger the oil-circulating ducts are, the less likely are they to hold sludge. Small ducts seem to have a compound effect on sludging. It appears inadvisable to filter oil in service when the inside of the case, carcase and the ducts are well sludged. The remedy should be more drastic, namely, removing the oil and washing all parts with a sludge solvent. Do the authors recommend forced oil circulation or forced water circulation for transformers? My experience is that the former is the better method.

Mr. W. R. Davies: With regard to voltage-testing, using sphere spark-gaps, can the authors say what is the ratio between a.c. and d.c. pressures as measured by means of spark-gaps, especially with various waveforms? I have experienced in the case of a 50-cycle, 50-kVA three-phase transformer a decrease of 15 per cent in the iron loss as compared with the maker's figures, using the 2-wattmeter method of measurement. Could this large difference be due solely to the waveform of the testing machine?

Mr. H. G. Weaver: The authors mentioned that resonance tests are sometimes carried out on transformers, and I should be glad if they would give a description of this test, as the conditions causing resonance in high-tension systems are difficult to reproduce on the test-bed. About 20 years ago a number of transformers were supplied to a certain railway company by a manufacturing firm with which I was connected. These transformers were installed in positions, in some

cases several miles, from the switches controlling them on the hign-tension side, and although they had been very severely tested at the works and gave no trouble there, they nearly all broke down immediately they were switched in. In every case the failure occurred in the end coils of the high-tension windings to which the terminal leads were attached, a number of turns being short-circuited. The trouble was traced to resonance effects and was completely cured by incorporating charging resistances with the switches. As the makers do not always know the conditions under which the transformers will be used I consider this test to be a most important one.

Mr. W. F. Chamen: I notice that the authors recommend that transformers should be overhauled at least every 18 months. It has generally been the impression that, transformers being static machinery, they should not require such frequent attention. Is oil the only liquid which has been utilized for cooling purposes?

Prof. D. Robertson: Have any experiments been made with regard to the use of carbon dioxide or other inert gas to keep the oil from contact with the air?

Mr. T. E. Lewis: Is there any difference between the tests taken on transformers for use in this country and those that would be installed in the tropics? There is a difference of from 70 to 80 deg. C. in the temperatures of working conditions.

Mr. W. J. Bache: What steps do the authors take to detect the presence of areas of excessive temperature in transformers, and do they recommend fitting large transformers with embedded temperature detectors?

Mr. S. Ogden: The need for periodical testing of the insulation resistance between primary and secondary and to the core is generally recognized. Is the oil as good after filtering as before, and, if not, how often should it be renewed?

Mr. R. Hodge: With regard to the use of centrifugal separators, what do the authors think of the desirability of using such a separator on a transformer in service? Would they recommend the use under such conditions of a special settling tank containing a reserve of oil? Do they consider that the installation of centrifugal oil purifiers with proper settling tanks in connection with transformers would tend to prevent the sludging of the oil in the transformer tanks?

Mr. O. Wheeler: The authors state that in the case of a transformer which had sludged badly it is not advisable to fill with new oil. Is the reason for this any special action of the new oil on the sludge still adhering to parts of windings which cannot be removed, and, if so, would it not be better practice to re-fill with the old oil filtered and cleared?

Mr. C. H. Cossens: If a transformer has become sludged is there any means of clearing it other than taking the transformer to pieces?

Mr. W. Nairn: Is there any agreement between the makers of transformers in this country with respect to polarity? The work of replacing a transformer with one of any other make and size ought to be purely mechanical, and if the makers agreed on a standard polarity test the work of the mains engineer would be greatly facilitated.

[The authors' reply to this discussion will be found on page 544.]

North-Eastern Centre, at Newcastle, 22 February, 1926.

Mr. F. H. Williams: Anyone acquainted with transformer-testing methods before the war, or even immediately thereafter, cannot but be impressed, in reading the paper, by the advances that have been made in the methods of carrying out routine tests. It has long been appreciated that iron-loss measurements are liable to considerable errors due to wave distortion, and the authors are therefore to be congratulated on developing a workshop method suitable for routine testing which will enable us to determine the amount of correction to be applied. They give an example where the wattmeter reading had to be corrected by 50 per cent. I had, a few years ago, some 7 800-kVA 20 000-volt, 25-period transformers to test, which gave an iron loss of about 14 kW. The guarantee was 22·5 and the calculated figure 21 kW. The wattmeters were checked and found to be accurate, but as an oscillograph was not available the wave-form could not be checked and the discrepancy was never definitely accounted for. It would now appear that the low figure was undoubtedly due to wave distortion. In connection with the measurement of ambient temperatures, I am glad to note that the authors advocate the immersion of the thermometer in a separate tank of oil. This is a much more satisfactory arrangement than that generally adopted of measuring the air temperature direct, and it is difficult to understand why it has not been adopted as the standard method. The tank of oil used for the purpose should, of course, be sufficiently large not to be affected by any temporary fluctuation of the surrounding air temperature. I regret that the authors have not told us anything about the measurement of "hot spot" temperatures. The tendency nowadays is to run alternators and transformers, etc., not on their rated output, which must be based on the assumption of the maximum ambient temperature, but on their actual temperature-rise, which, after all, is the more scientific and logical method, and, if full advantage is to be taken of this, accurate information regarding "hot spot" temperatures is essential and also a suitable method of giving warning when the limiting temperature is being approached. The authors make a passing reference to dielectric-loss tests. I consider that the possibilities of this test are not properly appreciated, especially in connection with the high voltages now used, and I should like to ask the authors whether they have any knowledge or experience of this test as applied to transformers, or of the magnitude of loss to be expected. They do not make any reference to the testing of tanks or terminals and bushings, all of which tests are of considerable interest to the purchaser. The crest voltmeter described in

the paper is of special interest, and the importance of using some such voltmeter in conjunction with a protective spark-gap to measure the voltage on the high-tension side cannot be too strongly emphasized. The practice, at one time fairly common, of measuring the voltage on the low-tension side of the testing transformer is sometimes not only very misleading, but dangerous. I made some measurements in connection with 20 000-volt 1 000-kVA core-type transformers and found that the charging current reduced the low-tension voltage necessary on the testing transformer for the pressure test by about 40 per cent. I am sorry that the authors have confined themselves to "the main tests carried out every day in connection with transformers." Whilst such routine tests are most important and are all that the ordinary purchasers of standard transformers of normal size and voltage can expect his apparatus to be subjected to, there are other special tests which are of great interest and of vital importance to engineers who require transformers for extra-high voltages or for connection to large power networks. The failure of such a transformer, apart from the local disorganization, may have far-reaching effects, and it is therefore necessary to specify that such transformers should comply not only with the ordinary standard tests but with other special tests. The first of these is the short-circuit test. All transformers for use in power stations or on large power networks should be capable of withstanding without damage a dead short-circuit across their secondary terminals, with the supply to the primary terminals maintained at full voltage and the high-tension oil switch set for instantaneous trip. This may sound a very severe test, but in actual practice a well-designed transformer has not the slightest difficulty in meeting it. Another important test is one to determine the factor of safety of the insulation between turns and between coils. To carry out this test special coils, exact duplicates of the transformer coils so far as the size of conductor and thickness of insulation are concerned, have to be made and tested to destruction. Research has proved that, in abnormal working conditions, the full line voltage is often applied across a comparatively small portion of the primary winding; hence the importance of this test and the reason for specifying for such transformers special reinforcement of the end turns. There is a test for another operating condition which I think our British manufacturers will have to develop, and that is a test to prove that the transformer will deal with surges and similar phenomena. The authors mention this test, which is known as a surge test, but so far as I am aware it has never been used except experimentally in this country. I believe that transformer breakdowns due to surges are, so far as this country is concerned, very few and far between, and it may be argued therefrom that such a test is unnecessary. The reply to such a contention is that in this country transformers are usually connected to cables, which, it is well known, are most effective in damping out surges and thus taking this form of shock off the transformer. With the increased use of overhead lines and higher transmission voltages, for which cables are not at present available, the direct connection of transformers to transmission lines will become more common and the need for a surge test imperative. In a copy of the German V.D.E. Rules, 1923, for testing transformers, a form of surge test is described in which oscillatory discharges are produced in the transformer under test by connecting one side to a condenser battery and spark-gaps while the other side is connected to the a.c. supply. I should like to ask the authors whether they have had any experience of this test and whether they can confirm that it is definitely specified as a standard test by the V.D.E. or merely as a suggested test.

Mr. W. T. Maccall: Do not the authors think that the wattmeter compensating coil (page 509) is liable to increase the error due to the inductance of the pressure circuit, which is particularly large at low power factors? Would it not be better to omit this coil and apply a correction to the wattmeter reading, calculated from the voltmeter reading? Fig. 11A would be clearer if the upper part were turned through a right angle to make A, B, C parallel to the corresponding current vectors in the lower half of this figure. In my opinion the authors have not made clear what they mean by "main flux" and "return flux." The flux in any limb has only one value, though it may of course be divided into components in any way desired.

(*Communicated*): The following alternative method of explaining the results appears to me to give a clearer and more accurate account of the phenomenon.

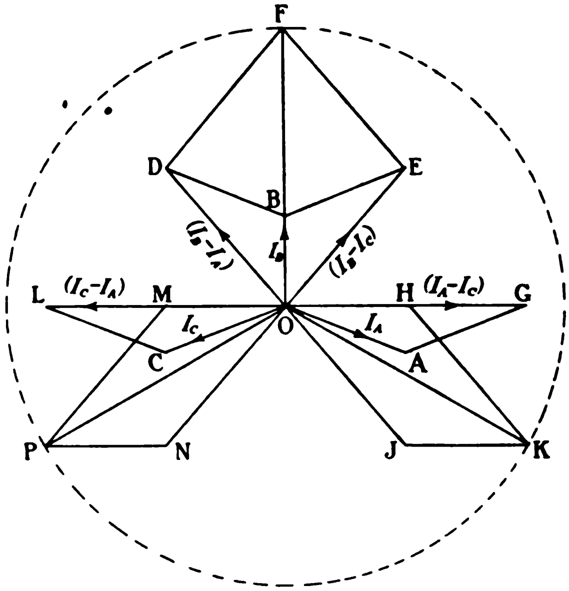


Fig. A.

In Fig. A the vectors OA, OB, OC represent the currents in the three windings (cf. Fig. 11A), neglecting the iron-loss components. OD is the vector difference, $I_B - I_A$, and so gives the M.M.F. and the flux in the circuit up limb B and down limb A (Fig. 9). Similarly OE gives the flux up limb B and down limb C. The vector sum, OF, of these two fluxes gives the total flux up limb B. Again OG, the vector difference $I_A - I_C$, gives the M.M.F. in the circuit up limb A and down limb C. But the flux in this circuit is only OH; where

OH/OG = (reluctance of circuit through limbs A and B)/(reluctance of circuit through limbs A and C). OJ is OD reversed, i.e. it is the flux up limb A and down limb B. The total flux up limb A is OK, the vector sum of OH and OJ. Similarly by adding OM (the reverse of OH) and ON (the reverse of OE) the total flux, OP, up limb C is obtained. The three resultant fluxes OF, OK, OP, are equal and at 120° to one another. The relative reluctances of the two paths (for the same case as worked out by the authors) is by this method very nearly 2 : 1, though this would be modified if the iron losses were taken into account. The remainder of the argument follows the same lines as in the authors' method, and the result is the same, but I submit that my method provides an explanation which is easier to follow.

[The authors' reply to this discussion will be found on page 545.]

North-Western Centre, at Manchester, 2 March 1926.

Mr. B. G. Churcher: The authors point out that accurate results are essential in the commercial testing of transformers. With this I fully agree. It should, however, be realized that the taking of careful readings on accurately calibrated instruments does not of itself ensure accurate results. In discussing any measurement, it is necessary first to define the quantity it is desired to measure and then to show that the method it is proposed to employ yields the desired quantity. In considering the subject of "ratio" measurements the authors speak of "voltage or winding ratio," but do not make it clear which they propose to measure. The ratio which is required for practical purposes is the no-load voltage ratio at full voltage. The three methods described, viz. the voltmeter method, the standard transformer method and the resistance potential-divider method, all measure the voltage ratio at the voltage employed during the test, which does not generally exceed one or two thousand volts. It is therefore necessary to consider whether a low-voltage test is admissible for high-voltage transformers. Consider the case of a transformer worked at a fairly high core induction and having considerable reactance. At full voltage, owing to no-load leakage, the primary and secondary windings will not enclose the same flux. At any voltage below about 80 per cent of normal voltage, the no-load leakage will become negligible and hence the flux enclosed by the two windings will be equal. Hence a low-voltage test will not give the voltage ratio for full voltage. It will, however, give the turns ratio with a fair accuracy. Another condition arises with very high-voltage transformers. It is well known that when such a transformer is excited from the low-tension winding, on the high-tension side a voltage exceeding that corresponding to the turns ratio is obtained. This is due to the large distributed capacity of the h.t. winding. The charging current, flowing through the reactance of the two windings, causes an appreciable voltage-rise. Now if the transformer is excited from the h.t. side, the charging current has a path of much lower reactance to flow through, and hence a smaller voltage-rise takes place. Thus the voltage ratio of such a transformer will not be equal to the turns ratio, and it will also depend upon which winding the testing voltage is applied to. The voltage ratio will probably not vary with the value of the testing voltage, since the reactance and distributed capacity are sensibly constant. From these examples, it is seen to be necessary to discriminate between the various "ratios" that may be measured. Of course in many, perhaps most, practical cases the effects discussed above may be negligible, but evidence on this matter is needed. In any authoritative survey of methods of testing such considerations should be dealt with systematically, as it is only by taking a comprehensive view of a problem that satisfactory methods of testing can be evolved. There is no technical difficulty in measuring voltage ratios at full voltage. With regard to the correction of iron losses for wave-form distortion, the reason why hysteresis loss varies with form factor for a given applied R.M.S. voltage is that the maximum induction varies with the form factor. For a given maximum induction the hysteresis loss does not vary appreciably with form factor. On the other hand, for a given induction the eddy loss varies as the square of the form factor. Since the greater part of the total loss in a modern transformer consists of hysteresis loss, it is best to arrange test conditions so that the normal hysteresis loss is obtained, and then to correct for the effect of form factor on the remaining eddy loss. Thus:

$$W = hfB^x + ef^2F^2B^y$$

where W is the total loss, h and e the hysteresis and eddy coefficients respectively, f the frequency, F the form factor, and B the maximum induction. If E is the normal R.M.S. voltage, the mean voltage E_m which should be applied to obtain the normal B is given by $E_m = E/1 \cdot 111$. This mean voltage can be applied by the use of a mean-voltage voltmeter. For a given mean voltage the induction in the core is independent of wave-form. Since the hysteresis term is unaffected by form factor, the normal hysteresis loss is obtained whatever may be the form factor, provided there are no inflections in the flux wave causing subsidiary hysteresis loops. Such inflections only occur under conditions of extreme wave-form distortion. Thus, so far as the hysteresis loss is concerned, there is no need to measure the form factor, but the latter is required for correcting the eddy loss. The eddy loss under the test conditions must be found by separation. The best way to do this is to keep B constant by means of the mean voltmeter and to take readings at two or more frequencies. The eddy loss is then corrected inversely as the square of the form factor. This procedure only involves accurately-known or measurable quantities, and no assumptions as to how the hysteresis or eddy losses vary with B need be made, since B is kept constant. Referring to Table 3, it would appear that a hysteresis exponent of 1·6 has been assumed by the authors, as in the expression given on page 514, col. 1. Now there is nothing fundamental about the value 1·6. It is a

value which Steinmetz found to hold for iron at low inductions, and cannot be taken as a universal constant for all materials under all conditions. With the 4 per cent silicon steel used in transformers, the exponent may have a value of 1·6 to 1·8 up to $B = 10\,000$, 1·8 to 2·2 up to $B = 12\,000$, reaching values from 2·3 to 3·0 at $B = 15\,000$, after which the exponent decreases. The exponent not only varies with B, but also from sample to sample of what is nominally the same material. It is therefore a very unsatisfactory quantity on which to base corrections to transformer iron losses unless it can be actually measured on the transformer in question, which is usually impracticable. In addition to this, the authors' method of correcting for form factor involves a much larger percentage correction than is necessary. Thus in the example at the top of page 514, col. 2, the observed watts are 17 850, whilst the corrected watts are 24 200, a correction of 35 per cent on the observed watts. Now in the method that I have described, in which the eddy loss only is corrected for form factor, the correction for a form factor of 1·4 would consist of dividing the observed eddy loss by 1·59, which amounts to a correction of 8 per cent on the total loss. Thus the method involves a definite correction of only 8 per cent, whilst the authors' method involves an uncertain correction of 35 per cent. From the values I have given for the hysteresis exponent, it is evident that methods of separating hysteresis and eddy losses, based upon an assumed value for the exponent, are inadmissible. To sum up, in measuring transformer iron losses the mean voltmeter is the fundamental instrument and should be used to set the normal induction in the core of the transformer. The R.M.S. voltmeter is used as an auxiliary to obtain the form factor for the purpose of applying a correction to the eddy loss. With regard to methods of measuring the mean voltage, the authors' valve-rectifier commutator is very convenient for test-bed work. Where the voltage to be measured is not less than about 100, the 0·5 per cent accuracy claimed by the authors can undoubtedly be obtained. The main advantage of the method is that it can be applied to any source of supply and requires no adjustment such as shifting the brushes of a rectifying commutator. It is, however, not correct to say that the brushes on a rectifying commutator require great care in adjustment. With a properly designed commutator the adjustment is far from critical and is quite simple. With a well-constructed commutator the form factors of voltages from several hundred volts down to 0·1 volt may be measured to 1 or 2 parts in 1 000. With regard to the "iron loss voltmeter," it would seem that such instruments are unnecessary where a dependable "mean voltmeter" is available. The compensation effected by iron-loss voltmeters is only approximate and the performance of such instruments should not be taken for granted. With regard to the statement on page 517, that the losses in magnetic shunts are inseparable from the total stray losses on short-circuit, the losses in such shunts can be obtained from the rate of increase of temperature of the shunt (measured by a thermo-couple) when the current is switched on, and the thermal capacity of the shunt, which can be calculated from its dimensions.

Mr. E. T. Norris: Insulation resistance is not mentioned in the list of tests required on transformers. At the present time most transformers are impregnated with some insulating composition, either liquid or solid, and it is necessary to dry the transformer out before it is impregnated. I am not sure whether the authors are describing the drying-out process before this impregnation or after, unless the transformers are being impregnated in their own oil. If not, and it is presumed the transformers have been properly dried out before impregnating, I do not think that 11 000 volts is a necessary limit for drying-out without vacuum. There would not be much moisture inside the insulation if it had been recently dried out before impregnation. I am very glad that the authors emphasize that a single measurement of insulation resistance with a megger with the transformer cold is no criterion of dryness. Where a transformer is being dried out in oil I think that a single measurement of the insulation resistance is no criterion, even if done with the transformer hot. In a works, however, air drying out is nearly always used. It is simpler and more effective, as the authors suggest. In Fig. 2 on page 507, in the diagram of temperature, vacuum, etc., the authors mention a vacuum of approximately 28 in. I assume that is based on a 30-in. barometer reading. It means that the vacuum is within 2 in. of perfect. For a large and high-voltage transformer, such as is indicated in Fig. 2, I should consider that poor. It is fairly safe to assume there is eight times as much air left inside the insulation with 28 in. of vacuum as with $29\frac{3}{4}$ in. or within $\frac{1}{4}$ in. of perfect. It is quite practicable to get within the latter value. The authors base their criterion of whether a transformer is dried out by plotting the curve of insulation resistance against time. I agree that that is a simple and very excellent way on a small, ordinary-voltage transformer, but for a high-voltage transformer it is possible to have a megger reading of infinity, and still not have the insulation dried out. The insulation resistance ought, at least, to be supplemented by some more sensitive method of moisture indication, such as a suitably arranged condenser. In this connection I am referring to transformers for voltages of 80 000, 100 000, or 200 000. There is a small point on page 508. Towards the end of the second column the authors say: "With large transformers the magnetizing current is almost equal to the no-load current, but with small transformers there is an appreciable difference." I do not think this equality or inequality is essentially due to the size. It depends upon the magnetic rating and the quality of iron. Even with the higher power factor of 0·2 given a few lines further down, there is only 2 per cent difference between no-load and magnetizing current. Then the authors go into the measurement of iron loss and the correction for form factor in very great detail. They give two examples which I expect are intended to show very forcibly the method of correction: they certainly do not represent average conditions in a transformer testing department. If a single-phase transformer is energized with the secondary winding open-circuited, the current is heavily distorted, mainly by third and fifth harmonics. If the generator or source of power is unable to supply this distorted current and maintain its sine-wave voltage, then both pressure and current wave-forms are distorted and the conditions

are fairly complicated. In the first example given on page 514 the form factor is 1·4, and, as has been previously pointed out, it involves a 35 per cent correction to the measured iron loss. As a general principle a method of test requiring 30 to 35 per cent correction is undesirable if it can be avoided. It is, of course, not always possible for a works to install machinery giving a pure sine wave with very heavily distorted current for all testing requirements. Where necessary, correction must be made as the authors suggest, but for the greater part of the transformer testing-work such correction should not be necessary. I would point out that for large and high-voltage transformers the methods of correction suggested by the authors will give entirely wrong dielectric losses. These losses are beginning to be of great importance even in high-voltage power transformers, and are often a limiting factor in testing transformers for voltages of 300 000 or 400 000 upwards. The form factor of 1·4 in that first example means, if we take the most favourable arrangement for displacement of the third harmonic, a distortion of something like 40 per cent from sine wave-form. I think, however, that it is very useful to have had the importance of the sine-wave voltage pointed out, and the precautions necessary if we have to depart from it. On page 522, where the authors are considering the measurement of temperature by increase of resistance, they give two methods of obtaining the correct resistance after shut-down. One is by means of factors dependent upon the watts loss per lb. of copper; the other is by measuring the temperature some minutes after shut-down and extrapolating back. The factors given for correcting temperature by the watts loss per lb. of copper, although they have been accepted by many authorities as standards, are based on experiments made some years ago on transformers which were typical of the usual thermal ratings at that time; they are purely experimental figures and are not necessarily true for present-day types of thermal design. For this reason the agreement given by the authors between the two methods of correction is not in itself a guarantee of the accuracy of either. As regard the extrapolation method, it is extraordinarily difficult to extrapolate back from a curve of changing slope. I do not agree with the authors' faith in this method where it can be avoided. They give an example of a correction where the resistance was measured 3 minutes after shut-down. Now on a large transformer, or on any transformer, it is usually possible to get one reading, one measurement of resistance, within 2 or 3 minutes after shut-down, but very often it is not possible to get both readings—high-tension and low-tension windings—in that time, and as the time between the instant of shut-down and the first resistance measurement increases, the inaccuracy of the extrapolation method becomes very much greater. The extrapolation method also necessitates the instant shutting down of all the cooling methods, as the authors state on page 523. It is very difficult to do this, and it involves another inaccuracy in the extrapolation method. It is well to remember the disadvantages and limitations of these methods, although an accurate method capable of general application is not yet available. In certain cases it is possible to obtain correction by means of embedded temperature detectors, and for this purpose it is not necessary that they should record the hottest spot temperatures of the copper. This method is the most accurate, but is of very limited application at present. The paper deals in a comprehensive and full manner with a subject which is not often discussed in detail, and in future years it will be a valuable record of the present-day practice and progress in the testing of transformers.

Mr. J. L. Carr: Usually one regards the testing methods adopted on works' test-beds as being somewhat crude, and it is no uncommon thing to see instruments used indiscriminately with shunt and series transformers without any allowance being made for the errors that such transformers will produce upon the instruments. A paper of this sort, which emphasizes the necessity for carrying out measurements of this kind with a reasonable degree of accuracy, is very valuable to those engaged upon test-bed work. In this connection I note that the authors have adopted the use of a total current dynamometer wattmeter of the precision type for the measurement of losses. This, I think, is a great step forward. It is perhaps not generally appreciated that when measuring power at a low power factor of, say, 10 per cent, a leading phase angle of 1° in instrument transformers will produce an error of 100 per cent in the indicating instrument. In connection with the determination of the turns ratio of transformers, the resistance ratiometer would appear to be the most satisfactory arrangement, but the method is one which does not necessarily give a true indication of what the open-circuit voltage ratio will be in normal operations. There are one or two points in connection with this arrangement which I think tend to produce slight inaccuracies, and it will be interesting to have the opinion of the authors as to the magnitude of the errors produced. For example, with instruments of this sort it is necessary to take a certain amount of current from the potentiometer, and that in turn, unless the conditions are very nearly balanced, is apt to disturb the reading, although the error may be only a small percentage. Further, with an instrument used in this way, it is to be expected that the phase angle of the wattmeter will tend to give rise to slight inaccuracies. Perhaps they will not be commercially important but, nevertheless, they exist. The use of the iron-loss voltmeter is very interesting, but I fail to see the necessity for one of these instruments if a mean voltmeter is used. The calibration of such an instrument as the iron-loss voltmeter would, I think, be somewhat tedious. The method of measuring resistance described by the authors as being most suitable for transformers is by means of an ammeter and voltmeter. I have had some experience in obtaining cooling curves on various electrical appliances and I was somewhat surprised to see this method preferred to some of the other methods of greater precision in common use. Here we have two instruments with a minimum inaccuracy in reading which is of the order of 0·1 per cent, and the error may be in one direction in one instrument and in the other direction in the other instrument. Great accuracy is therefore out of the question. Further, the two readings must be taken simultaneously, otherwise, as the appliance cools down very rapidly, very considerable differences may be obtained. Personally, I should

strongly recommend the use of a Kelvin double bridge, particularly during cooling. It is possible by the use of such an appliance (which is available in portable as well as laboratory patterns) to obtain very rapid and accurate readings of resistance. Readings can be obtained, after the transformer is shut down, more quickly than by the two-instrument method, and, in addition—and this is of importance, particularly when looking for small changes in resistance—the accuracy of measurement is considerably higher if suitable precautions be taken.

Mr. H. Diggle: The resistance ratiometer described on page 508 seems to be simply an elaboration of the old potentiometer method for comparing the voltages of two primary batteries, etc. I do not see the necessity for introducing the wattmeter. A previous speaker has mentioned that there may possibly be a slight error in the instrument itself due to a small difference in phase between the fields produced by the moving and fixed coils. It ought to be quite a simple matter, without any loss of efficiency, to connect the high-tension winding of the transformer across the maximum resistance and make a common point between the high-tension and low-tension windings at one end. The other end of the low-tension winding could be taken through a sensitive a.c. ammeter to the other dial. On page 509 the two-wattmeter method and the three-wattmeter method are mentioned for iron-loss measurement of three-phase transformers, and, from the results given in Table 1, it could be inferred that the one method is equally as good as the other. The total for the two-wattmeter method is 1·112 kW as against 1·12 kW in the case of the three-wattmeter method. Also, the suggestion is implied that owing to the two-wattmeter method having a better power factor on the instrument, it may be an advantage to adopt this method, although this is not definitely stated. I think the fact that the two-wattmeter method depends upon the difference between two relatively large readings renders it open to greater sources of error, and that the three-wattmeter method is preferable, particularly now that the objections on the score of low power factor on the instrument can be got over by the use of the new low-power-factor type of wattmeters which are available. On page 516 the question of the separation of the eddy-current losses from the measured copper losses is mentioned. As Mr. Churcher has mentioned, the square law is of rather limited application. I have applied it to several cases, and, in general, have found that on a transformer which has a comparatively low percentage of eddy-current loss the square law will apply and a straight line will result when watts loss is plotted against frequency squared. If, however, a transformer is of bad design, or if for any reason the eddy-current loss is a high proportion of the total loss, my experience is that the square law does not hold and the index figure is nearer 1·5. Mr. Norris has mentioned that the form factor in iron-loss measurements is shown as having a rather bad effect in the examples. From these a purchaser may be rather liable to imagine that he may not get a true reading when the ordinary test is taken. In most cases it is possible to arrange that the generator from which the iron loss is supplied is so big that its wave-form will not be particularly distorted when supplying the magnetizing kVA of the transformer; and I consider it desirable to mention that such discrepancies as are indicated in the paper will only occur when a big transformer is being tested and its no-load kVA is somewhere near the full capacity of the generator supplying the loss. On page 519 mention is made of full-load temperature runs. It is said that "a single-phase transformer cannot in general be run on load by itself." This is strictly true of shell-type transformers only. With a single-phase two-leg core-type transformer it is possible to carry out a load run by treating the two legs as separate transformers, putting one against the other, and then upsetting the balance by boosting to circulate the load current. Fig. 19 (B) on page 519 shows two star/star-connected transformers with the phases crossed. Whilst this is not incorrect, it is not necessary. The diagram can be simplified by connecting the phases straight across between the two transformers. In Figs. 21 and 22, which show similar crossings, the crossing is necessary and the diagram cannot be simplified. The question of connections for temperature-runs on all types of transformers was the subject of a paper read before the Students' Section of this Centre some 12 or 13 years ago, and an exhaustive treatment of this section of the paper appeared in the *British Westinghouse Gazette* for March 1918. I think that the method of overpotential test shown on page 524, viz. superimposition of high-frequency and low-frequency waves, requires a little more explanation than is given in the paper. The real object of this superimposition is to reduce the number of peak values in a certain length of time, and it seems to me that the effect shown by the authors could be achieved equally well by having a generator with a badly designed (peaked) wave-form. The object of using a high frequency in overpotential tests is simply to keep down the magnetizing current. It seems to me that the voltage wave on the right-hand side of Fig. 26 should give a magnetizing current not particularly different from that which would result from a sine wave at fundamental frequency. Perhaps the authors will explain this point further. In connection with the measurement of iron loss of a three-phase transformer by the three-wattmeter method, I think there is a slight error in the readings shown in Table 2 at 300 and 280 volts. In the power-factor columns there is a generally steady sequence, the power factor varying in one direction as the voltage is varied. At 254 volts the phase power factor of phase A is 0·0350, then it rises to 0·0406 at 280 volts, and then falls to 0·0325 at 300 volts. There is probably an error in observation due to the difficulty of obtaining accurate readings at these high values of flux density in the core. I have done a number of tests of this nature and I think that Fig. 10 would have been more interesting if a curve of total watts had been added. This would have been found to cross the curve for phase C if carried sufficiently high. Another interesting fact is the way the three wattmeter readings vary as a percentage of the total watts loss. Fig. B shows the results of tests made on a standard three-phase core-type transformer. The three wattmeter readings are expressed as percentages of the total loss and are plotted against voltage. On low voltages phase A takes

45 per cent of the total, the other two phases taking 27½ per cent each. Phase B maintains its figure constant at 27½ per cent, but phase A increases its value with rising voltage, and phase C reduces its value and becomes negative above a certain point. The curves for phases A and C are symmetrical but in opposite directions. At 100 per cent volts phase C is zero, and if the voltage is carried to a point where it has become — 27½ per cent, the reading of phase A is equal to the total loss. At any voltage higher than this, the reading on phase A is greater than the total loss. The initial proportions depend upon the particular core, but will not differ

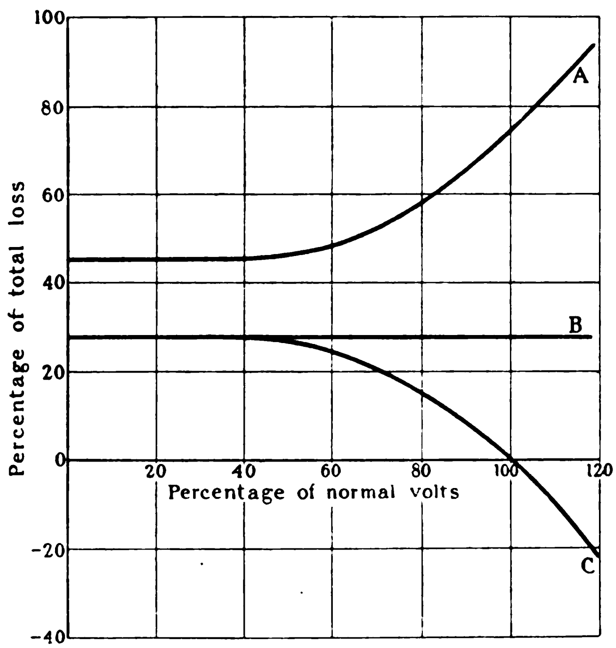


FIG. B.

much from the figures given. In the test given by the authors the figures for the three phases are A 48 per cent, B 27 per cent, and C 25 per cent.

Mr. A. Philip : With reference to the measurement of iron loss in three-phase transformers, and particularly to the case when the authors obtained a negative wattmeter reading in one phase, the transformer being quite symmetrical as regards the outer limbs it appears that either outer phase can give the negative wattmeter reading on no load, it depending entirely on phase rotation as to whether phase A or phase C does so. With reference to the vector diagram explaining the phenomenon, it would appear that the authors have set out to determine the total resultant flux in each limb of the transformer, but that they have later abandoned this plan in favour of using certain of the return-flux values to determine the phase relation of the currents in the three phases. With regard to the oil used in transformers during test, it is noted that the authors specify a breakdown value of 30 kV for a 0·15-in. gap, and I think it would be advisable that this figure should be adopted in B.E.S.A. specifications, as it is one which can be readily attained. The present figure of 22 kV is low enough to permit the use of an oil which is only of medium quality and which can be usually improved by centrifuging.

Mr. F. E. Hill : The authors have quite rightly stressed the importance of accuracy ; one of the chief factors in realizing this accuracy on the test bed is in the choice of testers who are suitable for this particular work. Routine transformer testing becomes very monotonous, and is only varied by special tests and tests on special apparatus. For this reason, unless the testers have a scientific interest in their work, carelessness may nullify the various precautions described by the authors to obtain a reasonable degree of accuracy. It cannot be too strongly impressed on the testers that, whilst production is important, it ranks second to accuracy as far as they are concerned. The authors point out the necessity of recording the temperature at which resistance measurements are made. It is equally important, of course, to do so when making copper-loss measurements. Customers' inspectors often have the copper loss measured after the temperature and insulation tests ; under such conditions it is difficult to ascertain the temperature of the windings without taking a further resistance reading, and, as this is rarely done, it is impossible accurately to correct the copper loss to the basic temperature. The copper loss should, wherever possible, be measured when the transformer has been standing at atmospheric temperature for a considerable period. I am surprised to find that the authors recommend the plotting of resistance against time and extrapolating to obtain the temperature-rise at the instant of shut-down at the end of a temperature test. The readings of resistance under such conditions which have come under my notice leave very much to be desired in this respect, as the first reading is rarely taken earlier than 3 minutes after shut-down, when the flatter part of the cooling curve is already reached. This is borne out by the figures in Table 6. If these had been shown in the form of a curve instead of a table it would have been seen why there had been little difficulty in obtaining results by this method which agree with the results by the alternative method to within half a degree. The alternative method of correcting by definite factors based on the rating of the copper and the time of the reading after shut-down was developed in America on account of the difficulty in obtaining accurate results by the extrapolation method,* and, although this method may not be strictly accurate, in the majority of cases it is probably the more accurate method. The method described by the authors of carrying out overpotential tests where a very high frequency is necessary is very interesting. The severity of such tests has been recognized in the latest edition of the American Standardization Rules, which now permit of a reduced length of time for the test if made at over 120 cycles per sec. ; for instance, at 240 cycles per sec. the test is for a period of 30 secs., and at 400 cycles per sec. for a period of 10 secs. It is to be hoped that similar figures will be incorporated in the forthcoming B.E.S.A. specification for transformers, as, although the authors' test is undoubtedly satisfactory, I think that the usual test for a shorter period of time will be looked upon by inspecting engineers with greater favour.

* V. M. MONTSINGER : "Cooling of Oil-immersed Transformer Windings after Shut-down," *Transactions of the American Institute of Electrical Engineers*, 1917, vol. 36, p. 711.

Mr. A. G. Ellis: I should like to emphasize what Mr. Norris said about the value of this paper as a record for the future. As has been pointed out by Mr. Hill, we are now testing regularly, in works, power transformers up to 20 000 kVA rating under full-load conditions, and up to working voltages of about 150 000.

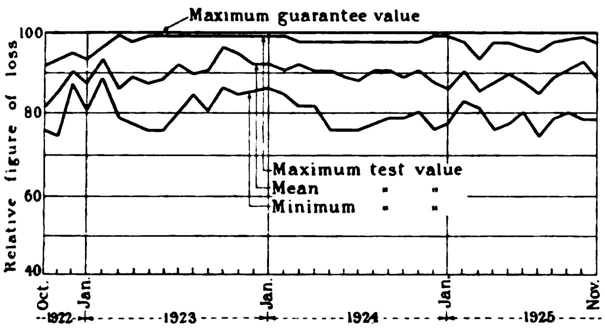


FIG. C.—" Figure of loss " for samples of transformer sheet-steel.

This involves generators for testing at normal frequency up to 3 000 and 4 000 kVA, from which one can visualize the size of the testing plant which has had to come with this development work. This matter is partly exemplified by the transformer referred to in Fig. 2, where the authors give data of the drying-out of a 7 333-kVA, 125 000-volt transformer. To give an idea of what is involved and of the time taken to dry out such a unit, I may point out that a transformer of this nature will weigh about 20 tons and will contain something like 2 tons of insulating material. This absorbs a tremendous amount of moisture in the course of manufacture, and the drying-out process is no light matter. I agree that the vacuum drying process is the best for such work. The authors say that air-drying is possible up to 11 000 volts. This doubtless refers to their method of drying transformers in a hot-air cupboard with steam-heated pipes in the bottom. Air-drying has, however, been used in America for very large and high-voltage units with a blast of hot air blown through the transformer itself. This is more applicable to drying-out on site, where one has not got all the facilities which are available in the factory, but wherever it can be done the vacuum process is probably the best. A good deal has been said about the accuracy of testing. One has to balance the expense of getting accurate testing in the shop with the results at which one is aiming. The object of shop testing is to check whether apparatus falls within its guaranteed performance figures. If it does so the customer is generally satisfied ; and extreme accuracy is really of secondary importance except to the designer, whom it will enable to make closer calculations on the next design. Now, apart from inaccuracy on test, there are a number of factors which cause wide variations in the figures produced. Variations in the uniformity of the material and in the workmanship, both in the core and in the winding, and so on, come in and play a very important part. To illustrate the variations in the quality of sheet steel for transformer cores, and the variations in the measured core loss on the finished transformer due to lack of uniformity in the quality of sheet steel and in the workmanship, I give in Figs. C and D measurements taken over a period of 4 years. Fig. C is a record of the figure of loss as measured on samples of sheet steel taken from bulk supplies from the manufacturers as received in the factory. The chart records the minimum, mean and maximum test-values and the maximum guaranteed value, above which latter limit the consignments are rejected. It will be seen that the maximum variation in figure of loss amounts to about 25 per cent. Fig. D is a record of the figure of loss (watts/lb.) on finished transformer cores on three different sizes of frame. Each spot on the chart represents a test on one finished transformer, the results being charted by

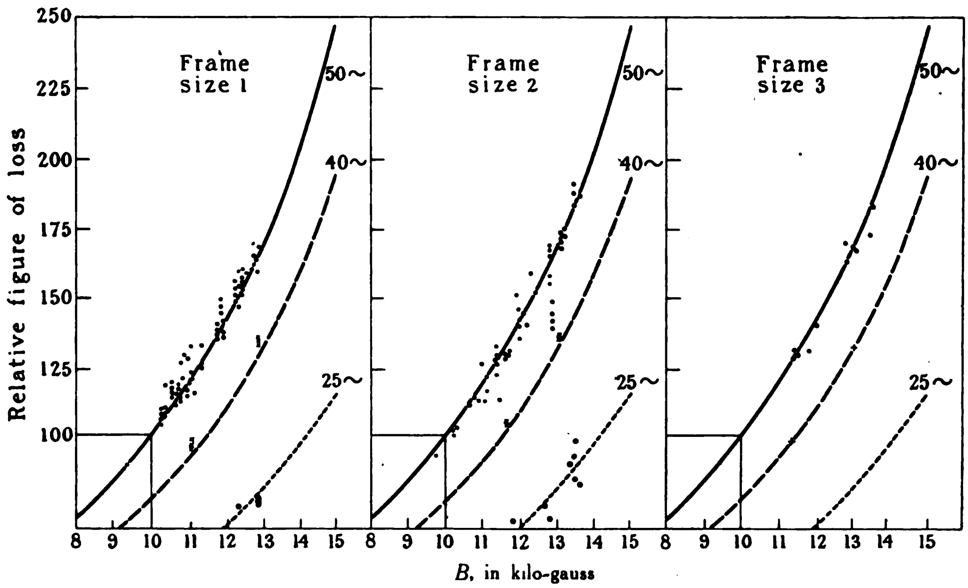


FIG. D.—" Figure of loss " for finished transformer cores.

plotting figure of loss (proportional to the watts per lb. of iron) against flux density in the core. The curves drawn for 50, 40 and 25 cycles represent the average curves which are worked to in designing. On the question of full-load temperature-runs, the authors have not mentioned the time taken for a very large unit to reach a steady temperature, which is often a matter of 20 to 24 hours. The time occupied in load-runs is a big factor in a works test-bed, and I should therefore like to ask the authors whether they advocate or make a practice of overloading these large units in the initial stages of the load-run; and, if so, whether they have had any experience of the danger of overheating the windings. The last point I will touch upon is the question of insulation tests on large high-voltage transformers with earthed neutrals. Where the neutral is earthed directly and permanently, the insulation test can only be applied by over-excitation. The American Rules specify in such cases a test at 2·73 times the phase voltage (i.e. the voltage from line to neutral). To do this it is necessary to raise the frequency in about the same proportion, as the authors have pointed out. Cases have come within my experience where a test voltage as high as 3·5 times the phase voltage has been specified. This means (on 50-cycle transformers) that we have to test with a frequency of 150 to 200 cycles. Mr. Hill has mentioned, in connection with tests at high frequency, that the breakdown voltage of the insulating material decreases with increasing frequency. For the materials usually employed the breakdown voltage at 200 cycles may be 20 per cent less than at 50 cycles. The strain on the insulation during test is greater than is often realized or warranted, and I would emphasize what the authors have said about a false sense of security being engendered by these abnormally high tests.

Mr. J. Longbottom (*communicated*): I should like to ask the authors what they consider to be the most reliable method of measuring the temperature on a transformer while it is being dried out under vacuum, as unless the element of the indicating apparatus is actually in contact with the transformer the true temperature of the latter will not be obtained, due to the absence of any heat-conducting medium. If vapour pressure-type thermometers are used these are liable to read low owing to the vast difference in pressure on the outside and inside of the bulb. I have found that thermo-couples soldered to pieces of copper which are bolted to the transformer core give the most reliable results, but considerable trouble was experienced in the upkeep of the insulation on the thermo-couples, since they had to withstand continuous working in dry heat. I am in thorough agreement with the authors on the method of measuring ratio, and have long since formed the opinion that the resistance ratiometer is the only satisfactory method of measurement. Ratio by voltmeter, though still used to some extent, leaves a large amount to be desired and should be avoided wherever possible. On the question of polarity I should like to ask the authors if they are acquainted with a three-phase polarity meter which will indicate such things as a reversed phase or incorrect delta connections, etc. I have not seen any instrument of this nature, but experience has shown that if one were in use on the test-bed, one cause of trouble on site would be avoided. I am rather surprised that the authors suggest obtaining polarity on a transformer by using direct current, with its attendant risks of shock, and would suggest that a far better method, though a very old one, is to join the tops of the l.t. and h.t. windings together, a convenient low a.c. voltage then being impressed on the two free ends. The voltage across the h.t. winding will then be greater or less than the supply, depending on whether the polarity is subtractive or additive. The authors do not definitely state which method of connection, two- or three-wattmeter method, is considered to be the better, but I think that the three-wattmeter method is desirable, since errors of observation are more likely in the two-wattmeter method, particularly where the supply to the transformer under test is of a fluctuating nature. The authors do not show any method of running a single-phase transformer by itself, and, in fact, they say that it must be run with either a duplicate or a larger transformer. I know of many cases where a single-phase transformer has been given a temperature-run by breaking the h.t. and l.t. windings into two equal parts and paralleling the like halves. A circulating current can be injected on either the h.t. or l.t. side and a magnetizing current applied across the l.t. windings; this, of course, should be equal to one-half the normal voltage. I have seen transformers up to 10 000 kVA and 100 000 volts run by this method. In using a spark-gap for measuring very high voltages the authors recommend a resistance of 1 ohm per volt, the best resistance being a column of water. I am surprised that water should be advised, as my experience has shown that as soon as the gap breaks down, if there is any delay in switching off, even if only 1 or 2 secs., the water is ejected with great force from the tube and falls on any apparatus that may be near. Wire-wound resistances can be obtained in sufficiently high ohmic values to be of convenient size and still have sufficient length to prevent a flash-over. I have seen very successful tests carried out with these wire-wound resistances. With regard to the authors' statement on page 526, col. 1, I do not consider it at all advisable that the grids should be left free, as they are liable to be charged to a potential sufficient to cause a breakdown to either the filament or the plate. I think that when the grids are connected to the plate there is far less risk of breakdown than when they are left free, even though the voltage from the plate to the filament may be lower in the latter case than in the former.

Mr. J. D. Peattie (*communicated*): I am very glad to note that the authors begin by insisting on a few elementary precautions to be taken, to ensure accurate and reliable tests. Incidentally, these precautions will amply repay the extra time and labour involved. That instruments should be cared for, checked and calibrated, may seem obvious when one reads it in cold print, but it is one of the points which do not always receive the attention they should. In a Continental test-room of which I have experience, well over 1 000 instruments were in constant use. These were controlled by an expert and a special staff. Every instrument was calibrated once a month (oftener, if necessary), and careful records were kept of its history, in addition to the calibration figures pasted on the case. The instrument-room standards

themselves were checked every year at the equivalent of the National Physical Laboratory and records kept of their behaviour. The unequal loss measurements referred to on page 511 in the three phases of a transformer can be regarded in another way, which I think may help to make clear the apparent anomaly. The energy stored in an ideal symmetrical three-phase field is constant in magnitude, although varying in distribution. In the case of the three-limb transformer shown in Fig. 9, its magnitude is not constant, but varies between a maximum and minimum value twice in every complete cycle. While it is increasing, additional energy has to be drawn from the supply, and while it is decreasing, the surplus energy is available for absorption by the losses, or, if more energy is available than these require, the balance is returned to the line. In the example given, phase C supplies the additional energy, and phase A benefits by the absorption of the surplus. The energy stored in the field varies as the square of the flux (or higher power if saturation is reached). The losses, as shown in the paper, vary as some power less than the square. The consequence is that the surplus energy available increases more rapidly with the voltage than do the losses, and on this account the input to phase A falls to zero and ultimately becomes negative as the voltage is raised, as shown in Fig. 10 and Table 2. With regard to heating tests, I should like to have the authors' views on testing for unequal temperature distribution. As the ultimate life of the insulation and oil may depend on this, it seems to me that some examination, on representative transformers at least, should be made in the test-room. In testing larger machines considerable trouble is taken to measure local temperatures, and it seems reasonable that one ought not to be satisfied, in the case of a transformer, with the measurement of average values only, as given by oil temperatures and increase in resistance of the windings.

The Authors' Replies to the Discussions at London, Bristol, Newcastle and Manchester.

Messrs. J. L. Thompson and **H. Walmsley** (*in reply*): Mr. Stigant in his remarks agrees with our views as regards accuracy, and this aim we have endeavoured to attain throughout the paper without the use of elaborate apparatus which, whilst it might be suitable for laboratory work, would be out of place on a modern works test-bed. The apparatus mentioned and described is such as is in everyday use on a modern test-bed, but it might be said that such apparatus has no definite finality since it is being improved upon in one direction or another month by month. We refer to and support the vacuum drying-out process, not because there are no other methods, but from the point of view of time and reliability. Time is one of the most expensive items in modern production, and must be reduced to a practicable minimum in order to obtain a maximum efficiency of output. The measurement of iron loss on transformer tappings is, in our opinion liable to serious errors, especially in modern transformers where, due to the high quality of iron available, it is possible to design transformers at high inductions, i.e. at values much higher than the bend of the B/H curve. Due to this fact it is necessary that the exciting ampere-turns embrace the full winding length of the core; otherwise serious flux leakage will result and thus cause erroneous readings. Copper-loss measurements of three-phase transformers are referred to by Mr. Stigant, who supports the single-phase and summation method. This method is approximately correct for small transformers with low reactance characteristics, but for large transformers, especially those of high internal reactance, it is liable to serious error. This error is due partly to the loss in a neutral lead being measured three times and also to the load leakage flux not being in its normal path as when measured three-phase. The use of static condensers for improving the power factor of machines giving load to the test has been mentioned. It is not a new suggestion, but we fear that their use, unless particular care were taken as regards their values, might lead to serious voltage-rises in some instances; and therefore to simplify the plant on a test-bed we do not recommend them. Mr. Stigant is disappointed at the absence of vector diagrams illustrating the tests. These diagrams are simple and can be easily drawn by those who are interested, but we do not think that they would have added much to the value of the paper, which is already of considerable length. Mr. Stigant states that the pressure-rises when pressure-testing are due to well-known phenomena. We agree, but we have stated that this rise must be taken into account, for the values obtained cannot be accurately calculated and, as the high-tension voltages for transformers are rising year by year, it is imperative for the manufacturers to provide means of measuring this high-tension pressure accurately. This provision ensures that no abnormal stresses are put upon the transformers on test, and thus eliminates the possibility of straining the insulation beyond the necessary limits. Mr. Stigant refers to the temperature-rise by resistance and by a thermometer in the oil; we agree that the difference in the temperatures thus obtained is not a definite figure for self-cooled units, though with artificially cooled units, such as water-cooled and oil-circulated, force-cooled units, there is a definite relation. The reason is found in the head of oil above the transformer in the self-cooled unit; the greater the head, the less the difference. Instances have occurred where the temperature-rise of the oil has been higher than the temperature-rise by resistance, which is, after all, only the average temperature-rise of the windings and not a maximum temperature-rise. There is possibly a definite relation between the average temperature-rise of the oil and the average temperature-rise of the transformer as measured by increase of resistance.

Mr. Melsom questions the accuracy of the megger as used for testing insulation resistance. We agree, if it were intended to use such an instrument for obtaining any actual insulation-resistance values. In the use to which we have put this instrument the accuracy of the actual figures obtained is unimportant as long as the figures

obtained with the same instrument are relatively accurate. In other words, as we have stated in the paper, it is not the value of the insulation resistance, but the characteristic of insulation resistance with time at constant temperature that is required. The period of time—60 seconds—given in the paper is suggested as being too low. If Mr. Melsom wishes, he may apply it for a longer period, but our experience, covering transformers up to 20 000 kVA and for service voltages up to 136 000 volts, has proved that up to these limits of size and voltage the stated time gives ample margin for a steady reading to be obtained, i.e. for the transformer condensers to be fully charged. With regard to the fall of the insulation-resistance value with oil immersion, the fall is immediate and Fig. 2 clearly demonstrates this. Our suggested method for obtaining resistance measurements comes under Mr. Melsom's severe criticism. We would point out that we are dealing with commercial and not laboratory accuracy, and whereas highly accurate instruments can be obtained in the laboratory, it is an entirely different matter when such instruments are used in a works test on commercial testing. It will probably interest Mr. Melsom to know that we have not made our statement in the paper without any foundation, for many methods have been used, as has been stated, and in each case the method has had to be abandoned. We think that most transformer manufacturers will confirm our opinion. Any bridge method of measurement, using high resistances to form the balancing limbs, are liable to errors due both to resistance changes with temperature and also to thermo-couple effects. The resistance elements and the copper or brass terminals constitute couples at different temperatures, and thus tend to upset the balancing. Although the bridge method is a " null " one, current is only nil in the bridge and galvanometer, while current is flowing in the arms of the bridge of which the transformer winding is one arm. This current is changing until balance is affected. Such balance is difficult to obtain, due to the inductive and capacity effects of the transformer winding. We have carried out experiments with a portable Kelvin double bridge, as suggested by Mr. Melsom, using several different values of resistance, and we found that to obtain an accurate result the greatest care had to be taken with joints and connections, far greater than that required for the method recommended, in order to obtain accurate values for the standard resistances and the resistances under test. Inspecting engineers frequently demand currents of relatively high values, such as one-third full-load current, for resistance measurements, and this demand leaves no alternative. With the double-bridge and similar instruments using a standard resistance for comparison, thermal effects are liable to occur if additional instruments are not inserted to regulate the current in the main circuits of the bridge. With regard to the time taken to obtain resistance values, the greater part of the initial time is taken up in the shutting down of supplies and cooling auxiliaries, and by taking care of surges produced by switching on the d.c. current to the inductive transformer winding as referred to on page 519. This occurs when using any other method and is generally independent of current value, due to the relative sensitivity of the instrument used.

Mr. Richards refers to the resistance-balance ratiometers and confirms their suitability, but states that they are not commonly used. We have three such instruments in daily use and have had them some two years. Mr. Richards is in error in his remarks about iron-loss voltmeters. We have two such instruments, but find their use and service very limited. The voltmeters have a very limited range, due to the fact that each instrument is only suitable for the frequency for which it is designed, and considerable errors are present when it is used on other frequencies. With regard to the form-factor examples for iron loss given in the paper, we wish to state that they are exceptional, although they are true tests picked out for demonstrating our point. The example with a form factor of 1·4 is exceptional and was due to the machine supplying the no-load kVA being of low rating, and also to the fact that single-phase load was taken from a three-phase machine. The other example with a form factor of 1·25 is quite a common occurrence when testing large single-phase transformers by loading one phase of a three-phase machine. Mr. Richards refers to resistance measurements. We have stated in the paper, and also carry it out in practice, that definite instruments should be set aside for resistance measurements and used only for that purpose. We state on page 519 under " Full-load temperature-runs " that there are many ways of approximating the load and losses, but those that are most nearly representative of true service conditions are here dealt with. To have described all the possible methods would have been too lengthy a task for a paper of this nature. Load running by the use of tappings is suggested by Mr. Richards as being a common practice. We ourselves never use this method, as it is rarely possible to find tappings equal to the impedance percentage of the transformers, and only an approximate load can therefore be obtained. Further, the generator supplying such a load is often severely loaded. Mr. Richards is surprised that we do not mention the hot-spot method. Unless Mr. Richards means the use of thermo-couples, we are at a loss to understand the point or test referred to. We suggest that the use of thermo-couples on standard tests is a dangerous procedure, from the points of view of the test-hand, possibly of the inspector, and of the transformer itself. They are dangerous because the hot spot is usually on or about the point of highest service potential, and it is not always possible to earth that point during a test run. Further, we suggest that thermo-couples if inserted and insulated do not necessarily give the exact temperature of the winding, due to the temperature gradient across the insulation between the conductor and the couple. We suggest that thermo-couples should not be used for standard tests but that they are of great service when used for investigation work, on transformers of new design, in order to give to the engineer information as to the efficiency of any particular method of winding and ventilation ; and that they should be limited to this service. For obtaining the maximum temperature we would suggest that the safest and best method for service conditions is the insertion of standard resistance elements in that part of the winding of a transformer which has been proved by exhaustive tests on similar

types to be the hottest spot. The increase in value of this standard resistance with the operating temperature of the transformer will then give the temperature-rise at that point. Such a scheme is outlined in Fig. E. Mr. Richards will probably be interested in an article on transformer temperatures in the *Electric Journal* (1925, vol. 22, p. 551).

Mr. Bloome refers to two methods of drying-out and is at a loss to explain the difference in the time taken. The insulation characteristic curve will be similar in both instances as Mr. Bloome states, but the rate of drying depends solely on the quantity of heat supplied and the method of supplying the same. Possibly the transformer dried out by short-circuiting had a very high internal temperature which is difficult to ascertain, and that possibly overheating and rapid drying have consequently taken place, with a risk of internal damage to the winding insulation. There should be no appreciable difference in the results obtained by the two- and

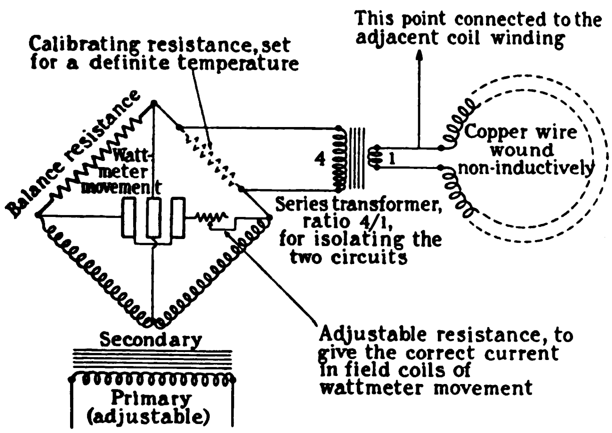


FIG. E.

three-wattmeter methods, provided suitable instruments and precautions are taken. The measurement of losses direct in the line is the safest procedure, notwithstanding calibration curves of instrument transformers. Cases do arise at times where a series transformer is essential for current values and also for safety, and in these cases precision instruments should be used and also two readings with reversed polarity, the average being taken. By studying the following figures it will be appreciated that series transformers may result in erroneous readings :—

Power factor	Error in phase angle	Error in measurements
		per cent
0·1045	30′	+ 7·7
0·2079	30′	+ 3·85
0·1045	1°	+ 15·4
0·2079	1°	+ 7·7

The method used for obtaining frequency readings depends on the size of the test plant. If the plant is small and the generators are close to the transformer under test a tachometer will probably give satisfaction. If the plant is large, however, and the machines are some distance away, then some distant-reading device is advisable to correct the frequency with load. The question of form factor has already been dealt with in reply to Mr. Richards. Mr. Bloome suggests that an ohmmeter is a satisfactory instrument for resistance measurements. We do not agree, however, as such instruments are affected by the unstable nature of the interlinked magnetic and electrical circuits, and time constants are almost impossible. For cold-resistance measurements the ohmmeter may be permissible but is not recommended, whilst for hot resistance where the circuit characteristics are continually changing it is practically inadmissible. The time required to obtain resistance measurements depends on the size and condition of the transformer under test; we do not state any limit but merely that the first reading should not be later than 3 minutes after shut-down. For pressure-testing, a motor-generator set is essential for true testing, even if an induction regulator be used; for the frequency of the test pressure should not be lower than that for which the transformer under test is designed.

Prof. MacGregor-Morris refers to crest voltmeters and bushing capacities. The following table will probably be a guide, though different makes and designs of bushings have different capacities:—

Bushing voltage	Capacity	Charging current for full-wave rectification
volts	μF	mA
500 000	approx. 0·000226	approx. 35·5
150 000	approx. 0·00022	approx. 10·35
110 000	approx. 0·00021	approx. 7·25
75 000	approx. 0·000138	approx. 3·25
36 000	approx. 0·000123	approx. 1·39

Further information on the above can be obtained by reference to the *Electric Journal* (1925, vol. 22, p. 571). We are very interested in Prof. Morris's remarks regarding experimental work on high-voltage measurement, using a neon lamp as detector or indicator, which is being carried out in his laboratories. The scheme seems to have possibilities, and further tests will probably perfect such a method of measurement.

Mr. Robertson refers to the open circuit of the grids in the crest voltmeter diagrams. It is fully explained in the paper on page 526. Three-electrode valves are used because they are easy of replacement, being commonly used in wireless work. If the grid is connected to either the filament or plate circuit the valve impedance is reduced. Lower readings are more accurate, but it is the higher readings that are required together with valve safety, i.e. a higher impedance, therefore on the instruments which we have in use—three in number—the grids are left insulated. We agree with Mr. Robertson's closing remarks.

Mr. Ockenden questions the possibility of obtaining a zero reading on the wattmeter movement used in the resistance ratiometer. There are, of course, limits of ratio to which the accuracy extends, but within the limits for which the apparatus is designed there is a

zero reading provided the ratios correspond. The method suggested by Mr. Ockenden is, of course, simple and accurate to a degree, but as it is a direct-reading instrument the same accuracy cannot be relied upon, for obvious reasons. For further sensitivity and to eliminate possible phase-angle errors as suggested, the authors have devised a thermionic valve balance to replace the wattmeter movement. This measures, in reality, the out-of-balance current flowing. Being a null method and also a polarized one, one can see at a glance whether the ratio is + or −. This method is shown in Fig. F, and we are now using, with satisfactory results, apparatus on the same principle in place of the wattmeter movement. With reference to this speaker's remarks relating to series transformers and static voltmeters, we still adhere to the statements in the paper. The 300 000-volt static voltmeter can be used, but its readings are liable to serious fluctuation depending on position, atmospheric condition, etc., and usually its readings are low.

Mr. Lacey questions the accuracy of the explanation under three-phase core-type transformers. We fail to

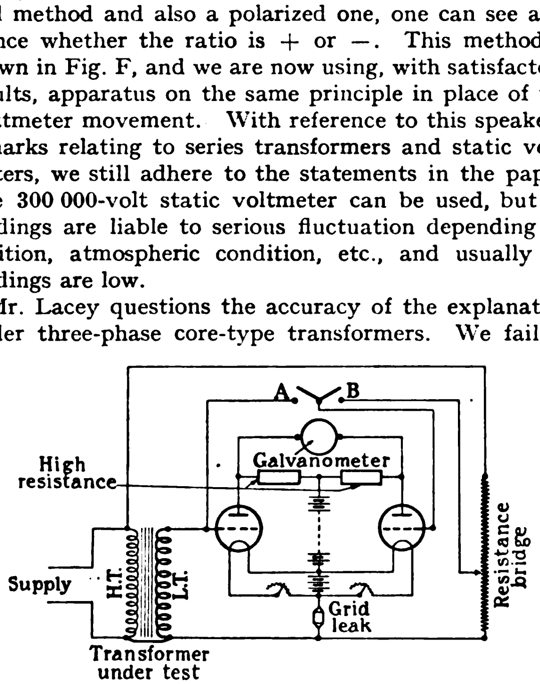


FIG. F.

see any error in our explanation however the transformer is connected, for it is based on actual physical conditions that cannot change. If Mr. Lacey had drawn a vector diagram to explain or illustrate other possibilities we think that he would reverse his decision.

Mr. Holbrook agrees with us on three-phase measurements and he points out the necessity for delta connection to be made when measuring losses. We agree, and especially is it necessary if three-phase shell-type transformers are in question. We are interested in Mr. Holbrook's method of load running, and should have been pleased if a diagram of the same had been included. The only objection that we see in this method is the capital expense involved in having to provide a phase-shifter and induction regulator. It means more auxiliary apparatus and probably two or three different sets and ratios, together with extra losses and therefore increased test charges.

Bristol Discussion.

In reply to Mr. Allan, several rough tests can be made on a defective transformer on site, depending on the voltage ratio and characteristics of the transformers. Megger tests might first be taken between windings, and between windings and the core, and if this gives no indication a useful test may be made by connecting the main supply across the two windings in series through a water resistance, or other means of limiting the current. Short-circuits will be indicated by excess current in the mains, and, if the cover is removed, bubbles and smoke will be detected rising through the oil. Some such test will generally indicate the trouble to be looked for when opening up. The conditions most conducive to the production of sludge in transformer oil are indicated by the standard tests on oil for sludge deposits. This is carried out by passing a current of air through the oil for 45 hours with the oil maintained at a temperature of 150° C. in the presence of bare metallic copper. Thus free air surfaces and high temperatures, together with bare copper, increase the sludging propensity of the oil. Periodical filtration of the oil reduces the risk of solidified sludging, especially when the oil is taken from the bottom of the tank and filtered into the top again. We agree that forced oil circulation is generally recommended, as the cooling device then becomes a separately controlled unit with oil under pressure, and so reduces the risk of water leaking into the oil; also the temperature of a force-cooled unit is more uniform and hot spots are less likely to be present.

In reply to Mr. Davies the sphere-gap functions on the maximum value of the a.c. voltage, although for convenience the gap is calibrated on R.M.S. values. Comparing d.c. and a.c. values, the d.c. flash-over voltage will correspond to $\sqrt{2} \times$ R.M.S. a.c. volts for sine wave only. To estimate this ratio for various wave-forms it would be necessary first to obtain the amplitude factor of the a.c. wave. Thus, amplitude factor = (maximum value/R.M.S. value). Mr. Davies does not indicate the size of the machine used for testing the 50-cycle 50 kVA three-phase transformer; as, unless this output was very small compared with the magnetizing kVA, it is improbable that form factor could account for such a difference. A 15 per cent decrease would represent a form factor of 1·22, a highly improbable figure for such a small transformer unless the wave-form of the machine on open circuit was very poor.

We would refer Mr. Weaver to our reply below to Mr. Williams in the Newcastle discussion with reference to surge tests. These tests are very indefinite and are not yet standard. Consumers can usually so arrange their cable system that such surges are negligible.

In reply to Mr. Chamen, the condition of a transformer can usually be judged by the state and amount of sludge in the oil; and, as filtration has now become an easy operation, were commend that each transformer be so dealt with at least every 18 months. Centrifugal separators of small size are now available, and these can be arranged to operate without removing the transformer from site. Oil is the only commercially successful cooling and insulating medium so far in use for transformers. Air-cooled (dry) transformers are in use up to 500 kVA and 10 000 volts, but for higher voltages and sizes oil is in general use, as the cost of large dry transformers would be prohibitive.

Experiments have been made by filling the upper reaches of the transformer tank with inert gases, as Prof. Robertson suggests. The American Westinghouse Co. have put on the market such a product in which the upper reaches of the tank are filled with an inert

gas and a breather attachment is fitted so that displaced gas due to breathing is replaced on cooling by chemical action in the breather.

With reference to Mr. Lewis's remarks, there are, in general, no special tests called for on transformers for operating in tropical climates. Special temperature-rises are usually specified and corrections made for special air temperatures and barometric pressures. Structural points have to be considered due to sudden changes of air temperatures, and usually these take the form of breathers or expansion chambers.

We would refer Mr. Bache to our remarks in reply to Mr. Richards, which cover the point he raises.

We agree with Mr. Ogden that periodic tests on site are a good insurance; the condition of the transformer can be gauged from such tests. Our experience is that transformer oil is quite satisfactory after filtration with modern filters. Centrifugal separators tend to drive off the lighter constituents of the oil, but no great change has been observed in its sludging value or electric strength. We cannot tell Mr. Ogden any solvent for sludge, which can only be wholly removed by stripping the transformer, but the major portion can be removed by a jet of oil at high pressure.

We would refer Mr. Hodge to our replies to previous speakers on this point, but would add that filtration while transformers are in service must be done with care. Large settling tanks are necessary for de-aerating the oil.

In reply to Mr. Wheeler, sludge in oil tends to accelerate sludging action, and so should be removed before filling transformers with new oil.

In reply to Mr. Nairn, we are unaware of any agreement on standard polarity, but we believe that it is under consideration at the present time by the British Engineering Standards Association.

Newcastle Discussion.

Mr. Williams refers to iron-loss errors. We agree that his assumption is now correct and that probably the error or low-loss measurement was due to the low kVA rating of the machine supplying the load, together with the single-phase loading of a three-phase machine. We note Mr. Williams's agreement with our method of measuring the ambient temperature. We actually immerse permanently a thermometer in a large glass bottle of transformer oil, which, being transparent, allows the temperature to be read easily without moving the thermometer or container. Mr. Williams has referred to hot-spot temperatures. This point has already been fully replied to and we would refer him to our reply to Mr. Richards in the London discussion. Dielectric-loss tests interest Mr. Williams, but we feel that they are as yet far from being accurate and cannot be called standard tests, and they have therefore not been referred to in detail. Much remains to be done in this connection and we hope to be able to continue tests on this subject and so add a little to the now scanty information. No reference is made to the testing of tanks or terminals, for these are not transformers but only auxiliaries and are tested in their respective manufacturing departments or factories. Mr. Williams's experience of pressure-rises when testing transformers some years ago was very common, but with the use of modern voltage-measuring appliances such errors do not now occur. Mr. Williams regrets that short-circuit tests have not been detailed. Such tests cannot possibly come within the scope of main commercial testing. Plant for such tests would be prohibitive and they could only be made on the mains or generators of large power supplies on account of the large kVA required. Surge testing is also referred to, and again we must submit that at present this does not in Great Britain constitute a standard test. Such tests are quoted in the V.D.E. rules up to a 60-kV rating for transformers. Tests of a similar nature are also carried out in Switzerland by Messrs. Brown, Boveri, and an interesting article on the subject will be found in the *Brown Boveri Review* for March 1925 (vol. 12, p. 47).

Mr. Maccall refers to the compensating coil of the low-power-factor wattmeter and suggests its elimination. The manufacturers of the instrument guarantee an accuracy of 0·1 per cent at 0·2 power factor with the compensating device, and this is quite satisfactory for commercial testing. The compensating coil is one of low inductance added to the field coils of the wattmeter to compensate for the current taken by the pressure coils of the instrument. With reference to the explanation in connection with Fig. 11, the terms "main flux" and "return flux" are used to clarify as far as possible the explanation and the relation of the reluctances to the return flux. In other words it is treated, as suggested, in component parts. Mr. Maccall's diagram (Fig. A) and explanation are interesting, but lead to the same conclusions and results as those in the paper. Whether the one method or the other is easier to follow depends to a great extent on the theoretical reasoning of the reader.

Manchester Discussion.

Mr. Churcher in his remarks on ratio measurement questions the meaning which we attach to ratio measurement. We intend to convey the idea that the ratio of the turns is to be measured accurately, and that is what is attained by the methods suggested in the paper. The full voltage ratio on no load and full load is, or should be, the designer's problem. The arrangement of coil design, the structure and dimensions of the core, and the flux densities to which the core is subjected, all influence the voltage ratio, more or less. In general, the ratios of the voltages and the number of turns are practically the same, and it is only in the case of extra-high-tension windings and high-reactance windings that a variation of ratio is apparent to any extent. Mr. Churcher takes us to task on our correction of iron-loss measurement for form factor. We know fully the reason for the errors to be corrected, but up to the present no satisfactory means have been available for making that correction on a commercial test-bed. Mr. Churcher suggests that the correction would be more accurate if the loss were measured on a mean voltmeter and the result corrected by adjusting the eddy-current component in proportion to the square of the induction. This method will give the same result as ours, which is dependent on the hysteresis exponent. We suggest first that

there is no "mean voltmeter" available except that which we have designed and which we term the "form-factor meter"; and secondly, that this method requires two corrections, one for voltage and one for eddy-current loss, whilst our method only requires one correction. Both methods require a separation of the losses curve and both require the same total percentage correction, though part of Mr. Churcher's correction is covered by the mean voltmeter or form-factor meter. Mr. Churcher has also queried the exponent used, namely 1·6, and so do we on page 514, col. 1, of the paper. The exponent used in the paper is Steinmetz's original figure and gave satisfactory results, but if there is any variation of this figure for different induction values, such figures could be used. The exponent of 1·6 is that obtained on numerous test samples at inductions of the same value as those used in transformer design. Further proof that this figure is approximately correct can be seen by studying the figures given in Table 4 on page 515. We agree that iron-loss voltmeters are not necessary where a good form-factor meter is available. With reference to the measurement of losses in magnetic shunts, we state in the paper that they are inseparable by any known test method, and to this statement we still adhere, for Mr. Churcher's suggestion resolves itself into a calculation.

With reference to Mr. Norris's remarks on impregnation, we include transformer windings which are varnish-treated and also those which are oil-impregnated; for drying out finally is essential in connection with both types of winding. We do not state that 11 000 volts is the limit for drying out without vacuum, but we give this voltage as a manufacturing limit where time and production are the limiting factors. Mr. Norris considers a 28-in. vacuum poor for high-voltage transformers. Probably he thinks that he is getting a perfect vacuum, but we suggest that a perfect vacuum is hardly possible, especially with varnish-impregnated coils. The vacuum will naturally depend on the atmospheric pressure at the time, the nature of the contents of the chamber under vacuum, the size of the pump and the container. We are quite satisfied with 28 inches, even for the highest-voltage transformer manufactured, for with this vacuum and a temperature of 75 to 80° C. any moisture present will be readily vaporized and extracted. Air drying is used for small transformers and in small manufacturing concerns, but where production is vital more up-to-date methods are employed. We have stated that a single insulation-resistance value obtained by means of a megger is of no value but is a guide when the transformer is hot, for if the transformer is damp the insulation resistance will fall rapidly when it is heated up. The insulation characteristics for very high-voltage fully-insulated windings are difficult to obtain, as stated by Mr. Norris, and in such cases experience is the only guide, dependent on the quantity of insulation embodied in the structure, which we can recommend. The condenser method suggested by Mr. Norris was tried by us some two years ago but with very indifferent results, and we therefore did not consider such a suggestion to be a practical possibility. Mr. Norris discusses the iron-loss correction; this has already been fully dealt with in our replies to Mr. Richards and Mr. Churcher. Mr. Norris suggests that our corrections for high-voltage transformers will give wrong dielectric losses. He quotes 300- and 400-kV transformers, but these are only special cases. The highest service voltage transformer made in this country is for only 136 kV. We agree that dielectric losses will have to be considered with high-voltage work, but we suggest they are a very small percentage of the no-load losses and so do not affect to any great extent our correction for form factor. Methods for separating dielectric loss from iron losses are not yet fully developed and provide a large field for future investigation. Mr. Norris has referred to resistance-measurements, and we would refer him to our reply to Mr. Richards and Mr. Melsom.

Mr. Carr refers to possible inaccuracies in the resistance ratiometer, and we would refer him to our remarks on the subject in reply to Mr. Ockenden in the London discussion. Iron-loss voltmeters and mean voltmeters are also discussed in our reply to Mr. Churcher. Resistance measurements have also been dealt with in our reply to Mr. Melsom.

Mr. Diggle does not see the necessity for the wattmeter movement. It is provided to enable one to see at a glance if the ratio is in error in a + or − direction. Further remarks on this point will be found in our reply to Mr. Ockenden. Further, the instrument suggested is altogether too insensitive. With reference to the separation of eddy-current losses from the total load loss, Mr. Diggle questions the square law of adjustment. If the windings are efficiently designed with conductors having reasonable section the square law for eddy currents holds good; if, however, abnormal sections are used we agree that the skin effect comes in and the index figure will be different, depending on the section. The question of iron loss has already been dealt with in our replies to several speakers, and further comment is unnecessary. On the question of temperature-runs on single transformers, we maintain that our statement is correct. As Mr. Diggle states, approximate load-runs can be carried out on single-phase core-type transformers if the leg-windings are balanced and treated as two single-phase transformers. High internal reactance will often result in these temporary connections, so that the load loss must be measured and full-load current must not be circulated or heavy losses will result and high temperatures be obtained. Over-potential tests are mentioned and superimposition is discussed, and a badly designed generator is suggested as an alternative. We submit that it would be waste of money to build a special bad-wave generator when the requirements can be obtained in simpler ways with standard apparatus which can be used for other test purposes. Mr. Diggle points out the irregularity of the figures in Table 2 at 300 and 280 volts; we agree that his assumption is probably correct and that the errors have occurred in observation.

Mr. Philip refers to three-phase core-type iron-loss measurements. We agree that upon the phase rotation depends whether the phase A or C is the negative reading; this is clearly seen if Fig. 11 is examined. We have not disregarded anything in our explanation of Fig. 11, for it is all bound up together. The return flux is quoted to show the effect of the reluctance of the

paths, and this in turn affects the magnetizing current. The oil-test values quoted in the paper are those used in our testing department, and no transformer oil is considered satisfactory unless it reaches the figure shown.

Mr. Hill stresses the point of test-hands having a scientific interest in their work. With this statement we agree. The only way to maintain this interest is to have test-hands with average technical ability controlled by a highly technical supervisor. Further, test-hands should be given every assistance by the designers, receiving full information of the tests required. Temperature measurements when taking copper or load losses are essential for accurate corrections to be made to the basic temperature at which the transformer is guaranteed. Resistance measurements appear easy to obtain, but in practice they are most difficult. This point has been raised by Mr. Richards and has been dealt with in our reply to his remarks. We agree with Mr. Hill's remarks regarding over-potential testing, and feel that some definite time-limit of high-frequency tests should be standardized and incorporated in the B.E.S.A. specification.

Mr. Ellis refers to air-drying for very large and high-voltage units and states that it is in use in America. We agree that it can be used satisfactorily, but from a production point of view it is not recommended as a shop or manufacturing process. This method is more adaptable to erection work where final drying after shipment is required. Accuracy of testing is referred to and we wish to state that we refer to the accuracy of the actual tests on the completed unit and not to the accuracy of the tests as compared with calculated figures. The diagrams given by Mr. Ellis show the difficulty which the engineer has in arriving at basic loss figures, and illustrate the possibility of accurate testing giving high or low losses when compared with estimated figures. The time taken to attain full-load temperature can be roughly gauged from the following values for self-cooled transformers:—

Up to	10 kVA,	50 periods	8–9 hours
	50 ,,	,,	9–10 ,,
	100 ,,	,,	10–11 ,,
	250 ,,	,,	11–12 ,,
	500 ,,	,,	12–13 ,,
	1 000 ,,	,,	13–14 ,,
	2 000 ,,	,,	14–16 ,,
	3 000 ,,	,,	16–18 ,,
	5 000 ,,	,,	18–20 ,,

The time required for the load-run maximum temperature can be reduced by starting up the transformers in hot oil or by starting with a 25 per cent overload for a period. The period of overload is limited by the possible hot-spot temperatures. If the temperature-rise is estimated at 50° C., then the overload can be maintained with safety until the transformer oil temperature reaches approximately 60 per cent of the final expected temperature-rise. If this period of time is carefully adhered to, no damage due to internal heating should result from an initial overload. Mr. Ellis, like Mr. Hill, refers to over-potential tests at high frequencies and we would refer him to our remarks in reply to Mr. Hill.

Mr. Longbottom asks for information on temperatures under vacuum. We gauge the temperature of units drying out under vacuum by distant-reading recording thermometers. The actual temperature of any unit is then obtained by a correction based on exhaustive tests taken, giving the distribution of heat in the chamber under vacuum. Mr. Longbottom agrees with our recommended method of ratio measurement. On the question of polarity the subtractive and additive method is quite in order, but high ratios and fluctuating voltage-supplies make it difficult to obtain wholly satisfactory results, whilst it is also not positive for three-phase measurements. We have no definite apparatus to suggest for three-phase polarity. With reference to the d.c. method, we do not suggest it but state that it is a means that can be used for obtaining polarity. We understand that it is almost universally used in the States. Methods of three-phase loss measurement are referred to. We claim that either method is equally accurate, and we use the method which is most convenient and suitable to the transformer under test. For fluctuating voltages we recommend in the paper an additional voltmeter for checking and maintaining the voltage constant during the test. Reference is made to load-runs on single, single-phase transformers; this has already been dealt with in our reply to Mr. Diggle. Mr. Longbottom comments on our recommendation of a column of water as a high resistance in a pressure test-circuit. Whilst a column of stationary water does behave in the manner suggested at times, yet the resistance of running water should overcome the difficulty. He also refers to the crest-voltmeter grid connections, and we would refer him to our reply to Mr. Robertson.

Mr. Peattie agrees with us in insisting on the necessity for elementary precautions. The elaborate checking scheme quoted is very interesting and shows the care which some manufacturers deem necessary. The descriptive explanation of the three-phase iron-loss measurement is of interest and will probably clarify the phenomenon to many who would otherwise be in difficulties. We would refer Mr. Peattie to our replies to several speakers on this point. We agree with Mr. Peattie that heat-distribution tests in transformer units should be investigated on typical examples of various constructions. Such tests are usually carried out by large manufacturers before putting forward any particular line of apparatus. For very large units such a course is financially impossible, and here it is necessary to base one's calculation on similar, though smaller, units. If the relation between maximum temperature and oil (or average) temperature is generally known for any particular type of construction, then we submit that Mr. Peattie's reasoning is quite sound and that oil temperatures and increase-in-resistance measurements should give safe evidence for judging the safety of the unit under full-load service conditions.

NEW METHODS OF IMPROVING THE SYNCHRONIZING TORQUE AND WEIGHT EFFICIENCY OF SELF-EXCITED SYNCHRONOUS INDUCTION MOTORS.*

By VALÈRE A. FYNN, Member.

(*Paper first received 24th April, and in final form 28th August, 1925.*)

SUMMARY.

Polyphase self-excited synchronous induction motors, including the latest types, are analysed with special reference to weight efficiency, conversion efficiency, and configuration of synchronizing torque. It is shown that the weight efficiency of such machines is low compared with that of polyphase asynchronous motors, because the secondary must be designed to carry polyphase load currents as well as unidirectional load and exciting currents. The alternating currents must be carried in a polyphase winding, the unidirectional currents in a single-phase winding. Although the latter may be a part of the former, it nevertheless follows that it is practically impossible to make the maximum synchronous torque of a given frame equal to the maximum asynchronous torque of the same frame. It is further pointed out that, even with a unidirectional and pulsating synchronizing torque, such motors do not run asynchronously with a sufficiently uniform peripheral speed of the revolving member to permit of the general utilization of their asynchronous overload capacity.

To overcome these drawbacks the author has conceived the idea of providing self-excited synchronous induction motors with a constant synchronizing torque, to run the machines synchronously from no load to a little beyond full load, and to run them asynchronously for all higher loads. The manner in which a constant synchronizing torque is produced is explained in detail and it is shown how the somewhat conflicting requirements of synchronizing torque and acceptable compounding characteristic are harmonized. Several embodiments of the resulting new motors are described, their synchronous performance being analysed by means of the circle diagram.

INTRODUCTION.

No synchronous induction motor, either self-excited or separately excited, can be manufactured at a sufficiently low figure and be successfully utilized in practice unless :—

(1) Its weight efficiency and conversion efficiency are high.
(2) It performs satisfactorily at starting.
(3) It synchronizes positively, without hunting and with a torque approximately equal to the maximum synchronous torque.
(4) It is automatically compounded so as to operate with a high power factor from no load to maximum load and, in particular, without ever taking an excessive leading current.
(5) It is capable of carrying overloads at constant or practically constant peripheral rotor speeds when operating as an asynchronous motor beyond its synchronous range.

The weight and conversion efficiencies are, of course, closely related and a figure as to one has little significance unless accompanied by the corresponding value of the other. The weight efficiency largely depends on the length of the air-gap and on whether or not the non-synchronous peripheral speed of the rotor is sufficiently uniform to permit of torque-demands exceeding the maximum synchronous torque being satisfactorily handled asynchronously.

It is quite easy to secure a satisfactory starting performance, and short air-gaps are of considerable assistance in this connection. Automatic compounding, i.e. automatic control of the quadrature component of the load current, is necessary in all machines which are to operate without constant attendance, and is imperative in the case of synchronous induction motors with standard induction-motor air-gap. Rationally-designed synchronous induction motors with short air-gap generally have a maximum synchronous torque amounting to some 60 per cent of the maximum asynchronous torque.

The configuration and magnitude of the synchronizing torque determine not only the quality of the synchronizing performance but whether or not the asynchronous overload capacity of the machine can be utilized. The importance of the configuration and magnitude of the synchronizing torque of synchronous induction motors cannot be exaggerated.

The author soon realized these conditions and directed his principal efforts to the configuration of the synchronizing torque. The first synchronous induction motors possessed alternating synchronizing torques of slip frequency or double slip frequency and equal positive and negative maxima. Whilst an alternating synchronizing torque will synchronize a motor it will not always do so without hunting, and this practically precludes the use of the machine as an asynchronous motor for any but the starting stage. The author's undirectional and pulsating synchronizing torque * eliminated the negative wave of the old synchronizing torque and made it easily possible to make the amplitude of the new pulsating torque equal to the maximum synchronous

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* See paper entitled "A New Self-Excited Synchronous Induction Motor," presented at the Spring Convention of the American Institute of Electrical Engineers, Birmingham, Alabama, April 7, 1924; also "Another New Self Excited Synchronous Induction Motor," presented at the Mid-winter Convention of the Institute, New York, February 9, 1925.

torque in machines with induction-motor air-gap. As a result his new synchronous induction motors are quite free from hunting during the synchronizing period, but asynchronous operation under overloads is still unsatisfactory, because so soon as the motor lapses into asynchronism the pulsating torque reappears. There is no danger of the motor coming to a stop, as is the case when the synchronizing torque is purely alternating, but the speed of the motor varies or pulsates continuously in an attempt to adjust the resultant torque, i.e. the sum of the pulsating synchronizing and of the induction motor torque, to the torque demand.

Having solved the problem of synchronizing and also of compounding (see the papers already referred to),

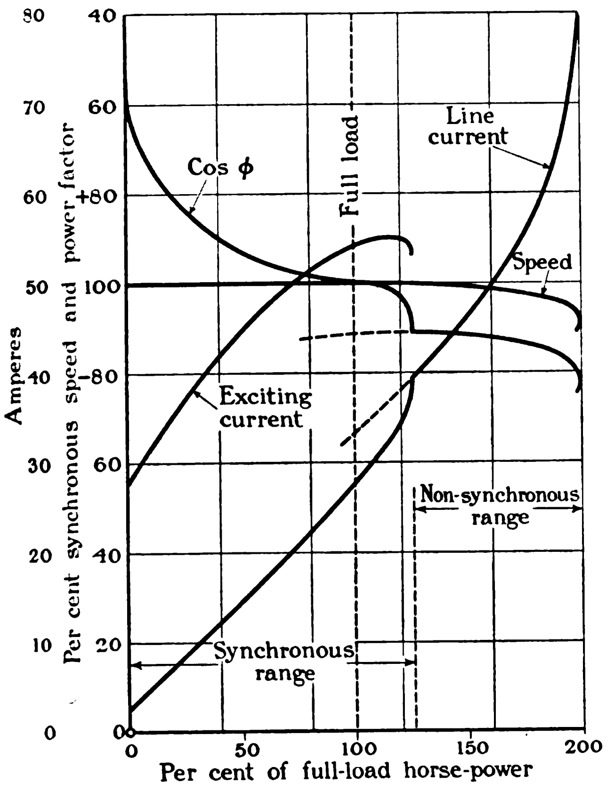

Fig. 1.—Character of performance curves of new self-excited synchronous induction motors (Fynn form 5).

the author addressed himself to the problem of increasing the weight efficiency of these machines. It occurred to him that the most natural way to achieve this was to render available for practical use the very large asynchronous overload capacity of such motors. If this could be done, then the machine could be designed for a maximum synchronous torque equal to about 60 per cent of the maximum asynchronous torque, and so rated as to cause the full-load torque to fall within a few per cent of the maximum synchronous torque. Under these conditions an overload would soon bring the motor to non-synchronous operation, and an overload capacity of some 100 per cent would be available. The character of the performance curves of such a motor is shown in Fig. 1.

Self-Excited Synchronous Induction Motor with Constant Synchronizing Torque.

The solution of the problem just outlined must be obvious to anyone who has read the author's Birmingham paper * and seen Fig. 37 therein. It amounts to producing two unidirectional and pulsating torques and displacing them by a quarter period, or producing three such torques and displacing them by one-third of a

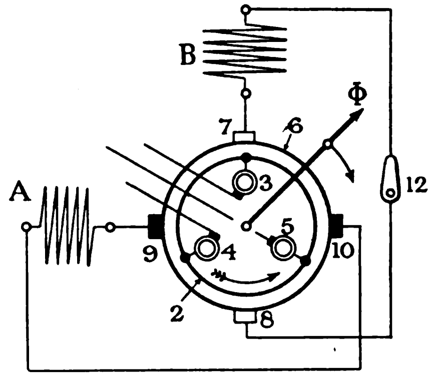

Fig. 2.—Elements and connections necessary for the production of a constant synchronizing torque in a self-excited synchronous induction motor.

period, and so on. Broadly speaking, it amounts to producing a polyphase synchronizing torque.

One way of producing a constant synchronizing torque in a polyphase synchronous induction motor is shown in Fig. 2. The rotor carries a primary winding 2 adapted for connection to a polyphase supply by means of the slip-rings 3, 4, 5, and a commuted winding 6 with which co-operates a two-phase arrangement of brushes 7, 8

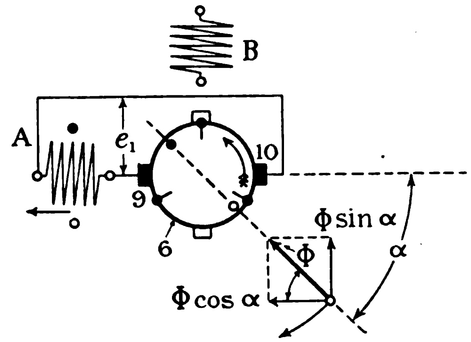

Fig. 3.—Showing how first component of constant synchronizing torque is produced.

and 9, 10. In order to eliminate all doubt as to the location of brushes with reference to the rotor and stator windings, they are supposed to be resting directly on the commuted winding 6. In practice a commutator would, of course, be used. The same clarifying assumption is made throughout this paper. The stator carries two identical windings A and B, displaced by 90 electrical degrees. The brushes 7, 8, are located in the axis of B and connected to it as shown. The brushes 9, 10, are located in the axis A and connected to this winding as shown.

* See footnote on previous page, col. 2.

Connecting the slip-rings to a polyphase supply produces a flux Φ revolving synchronously with respect to the rotor. If the connections are such that Φ revolves clockwise, as indicated by the curved arrow attached to the vector representing Φ in Fig. 2, then the rotor will revolve in a counter-clockwise direction. This revolution is due to the induction motor torque produced by the interaction between Φ and the currents generated in A and B by the relative motion between these windings and the revolving flux Φ. These secondary currents close through the brushes and the commuted winding. This induction motor torque starts the motor in the usual satisfactory manner and brings it near to synchronism. As the rotor speed

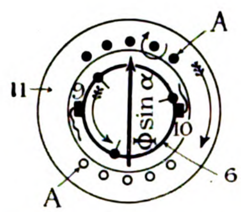

FIG. 4.—Diagram for determining direction of synchronizing torque produced by elements of Fig. 3 or of Fig. 6.

increases, that of Φ diminishes. At synchronism, Φ is at a standstill.

Very near synchronism the machine needs an additional torque over and above the induction motor torque which becomes zero at synchronism, in order to bring its rotor into synchronism. This additional torque is now known as the synchronizing torque; in Fig. 2 it is absolutely constant, as will be shown with the help of the following figures.

Consider what occurs near synchronism, taking one secondary winding at a time. In Fig. 3 the primary winding 2 is, for the sake of simplicity, supposed to

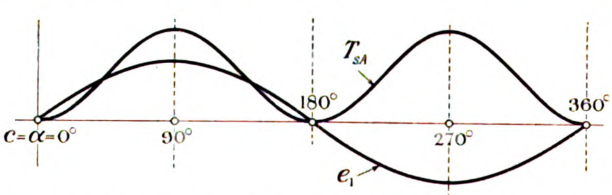

FIG. 5.—Configuration and phase of component synchronizing torque produced by elements of Fig. 3.

be combined with the commuted winding 6 and the slip-rings are not shown. B is disconnected, the rotor is supposed to revolve counter-clockwise at nearly synchronous speed, and Φ clockwise at slip speed—as would actually be the case in Fig. 2 just prior to synchronization.

Beginning to count time when Φ coincides with the axis of the brushes 9, 10, and is directed from right to left, consider the instant when Φ has travelled through α degrees. Because of the counter-clockwise rotation of the winding 6, the direction of the voltage generated therein by Φ is as indicated by the small empty and full circles. The empty circles indicate throughout an upwardly directed voltage or current, and the full circles the opposite or downward direction of either. The voltage e_1 appearing at the brushes 9, 10, sends a *conduced* current through A, distributed as shown by the small circles placed alongside of A, and produces a magnetization directed from right to left as indicated by the straight arrow. Let this direction of e_1 be positive. Because e_1 is of slip frequency the current for which it is responsible in A is practically in phase with e_1. The ampere-turns *conduced* into A, as against the ampere-turns *generated in* A by the relative motion between Φ and A, can and do produce torque in co-operation with Φ. This torque is independent of the induction motor torque superposed thereon and is here referred to as the synchronizing torque.

The magnitude of the synchronizing torque is always proportional to the number of ampere-turns in A and the concurrent magnitude of that component of Φ which is at right angles to the axis of A. These ampere-turns are clearly proportional to e_1, which is proportional to sin α. The effective component of Φ in this case is $\Phi \sin \alpha$, and the synchronizing torque T_{sA} due to A is therefore proportional to $\Phi \sin^2 \alpha$. It is clearly zero

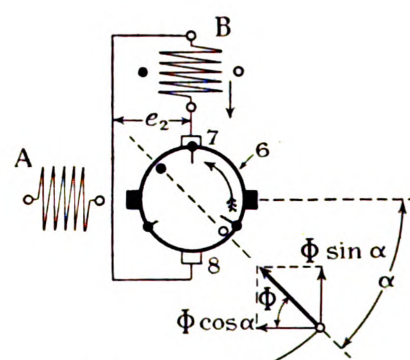

FIG. 6.—Showing how second component of constant synchronizing torque is produced.

for $\alpha = 0°$ and for $\alpha = 180°$, and a maximum for $\alpha = 90°$ and $\alpha = 270°$. The direction of T_{sA} may be determined by the ordinary electromagnetic rules with the help of Fig. 4. Under the conditions of Fig. 3, T_{sA} as exerted on the stator 11 is clockwise, whilst as exerted on the rotor it is counter-clockwise and positive since the rotor revolves counter-clockwise. It is also clear from Fig. 3 that T_{sA} remains positive for all values of α between zero and 180°. For greater values of α the polarity of e_1 reverses as shown in Fig. 5. This reverses the direction of the ampere-turns in A, but the effective component of Φ reverses its direction simultaneously, now pointing down instead of up as in Fig. 3, with the result that T_{sA} remains positive. T_{sA} is plotted in Fig. 5 together with e_1 for all values of α from zero to 360°.

Fig. 6 discloses what goes on simultaneously in so far as the winding B is concerned. For the same displacement α as in Fig. 3 the conduced ampere-turns in B are proportional to e_2, which is proportional to cos α. Let the now prevailing direction of e_2 be referred to as positive. In this case the effective component of Φ, that capable of producing torque with the conduced

ampere-turns in B, is $\Phi \cos \alpha$, and T_{sB} is therefore proportional to $\Phi \cos^2 \alpha$. The direction of T_{sB} can be readily ascertained with the help of a figure such as Fig. 4; it is clearly the same as that of T_{sA} and therefore also positive. It is further evident that T_{sB} is a maximum when T_{sA} is zero, and vice versa, also that T_{sB} remains positive when α exceeds 90°. Both e_2 and T_{sB} are plotted in Fig. 7 in correct relation to α. The resultant synchronizing torque T_s is the vectorial sum of T_{sA} and T_{sB}. It is shown in Fig. 8 and is clearly absolutely constant.

Having secured the desired constant synchronizing torque by means of the arrangement of windings and brushes shown in Fig. 2, the question arises, How will such a machine operate under load? The torque of

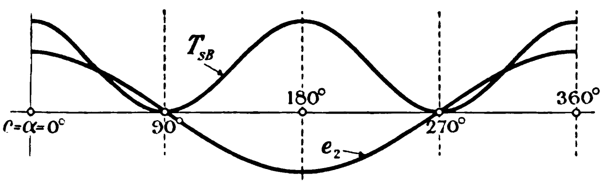

FIG. 7.—Configuration and phase of component synchronizing torque produced by elements of Fig. 6.

the motor depends on the magnitude of the projection of the resultant secondary ampere-turns N_s on the perpendicular to the resultant motor magnetization Φ, and an insight into the operation of the machine under load will be gained when it is known how the magnitude of N_s and its space relation to Φ can and do vary. The magnitude and space location of N_s depend on the magnitude and direction of the ampere-turns in A and B. At synchronism these depend on the brush voltages. The brush voltages e_1 and e_2 depend in turn on the position of the axis of Φ with relation to the axes of the two brush sets 9, 10, and 7, 8.

Referring to Fig. 2 and bearing Figs. 3 and 6 in mind,

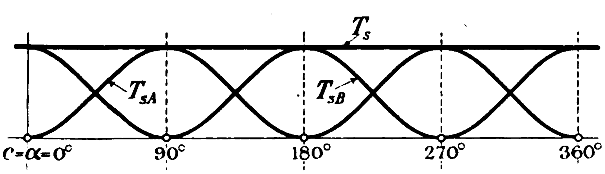

FIG. 8.—Constant synchronizing torque T_s resulting from proper combination of the component torques of Figs. 3 and 6.

when the axis of Φ coincides with that of the brushes 9, 10, and Φ is directed from right to left, the only stator magnetization is that due to B, and the ampere-turns N_B in B are a maximum; N_B lags 90° behind Φ. After Φ has travelled through 90°, the ampere-turns N_A in A are a maximum and those in B are zero; N_A now lags 90° behind Φ. Since the maximum ampere-turns in A are equal to those in B, and since the former vary as the sine while the latter vary as the cosine of any angle at which Φ is inclined to the axis of the brushes 9, 10, it is clear that the vectorial sum N_s of the conduced ampere-turns in A and B must be constant and that its axis must always remain at right angles to that of Φ, irrespective of the space position of Φ. Fig. 9 graphically depicts this condition. When Φ travels clockwise through 360°, N_s also travels clockwise through 360°, always keeping 90° behind Φ. This means that at synchronism the unidirectional ampere-turns on the secondary of Fig. 2 remain constant regardless of the space position of Φ, and that the synchronous torque is constant. Consequently there is but one load for which such a motor will run synchronously; the corresponding value of the primary ampere-turns N_p is shown in Fig. 9.

Nothing short of changing the machine or its constants will disturb the quadrature relation of N_s and Φ at or near synchronism. A departure from synchronism does, however, change the magnitude of N_s. At synchronism no voltage is generated in either A or B. At sub-synchronous speeds the voltages generated in these windings are of the same phase and sign as the respective impressed brush voltages, and the total ampere-turns in A and B increase, being due to the sum of the impressed and generated voltages in each circuit. At super-synchronous speeds the voltages generated in A and B are of opposite sign and now oppose the impressed or conduced brush voltages. As a result the ampere-turns in A and B are reduced. But torque is, in this case, proportional to the vectorial sum of the ampere-turns due to A and B, in other words to N_s.

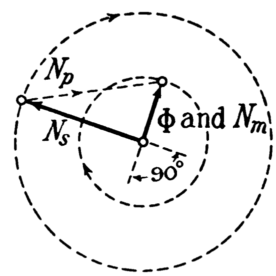

FIG. 9.—Diagram showing operating conditions of the motor of Fig. 2.

If the torque demand is less than the torque which corresponds to the synchronous value of N_s the motor must run super-synchronously at a speed at which N_s is reduced to correspond to the torque demand. If the torque demand is in excess of the torque which corresponds to the synchronous value of N_s, the motor must run sub-synchronously.

The machine of Fig. 2 runs synchronously only at one load and exhibits no compounding or power-factor-controlling characteristic whatever. There are, however, a number of ways in which it can be modified in order to make it operate synchronously under varying load, and to cause it to exhibit a practically useful compounding characteristic without sacrificing its most desirable synchronizing-torque configuration.

The simplest way to cause this motor to operate synchronously is to render one of the stator windings A or B inoperative upon synchronism being reached. This can be done, for instance, by interrupting the circuit of winding B of Fig. 2 by means of the switch 12.

Before determining the synchronous operating characteristic of Fig. 2 with the circuit of B open, it is well to fix upon some likely ratio of $N_{s.max}/N_m$, where N_m represents the ampere-turns required to produce Φ, and to base all comparisons between synchronous operating

characteristics on one and the same ratio of these values. Furthermore, since in dealing with synchronous induction motors one repeatedly passes from asynchronous to synchronous operation, and vice versa, it is as well now to fix our ideas as to the exact interrelations between those factors which control the asynchronous and those which control the synchronous operation of such machines.

In Fig. 10 is a current or ampere-turn vector diagram of a loaded polyphase induction motor. The primary current I lags ϕ degrees behind the terminal voltage E_t, and is the vectorial sum of the magnetizing current I_m and of a current $-I_2$ equal and opposed to the secondary current I_2. The current vectors can also represent ampere-turns and, in case of low densities,

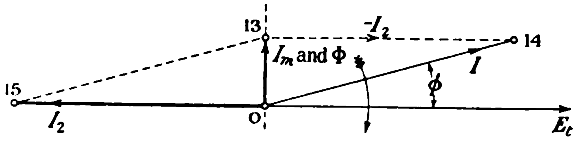

FIG. 10.—Vector diagram of loaded asynchronous motor.

they may stand for the magnetizations or fluxes produced by these ampere-turns. The facts that the flux Φ, the revolving flux produced by the primary, actually lags slightly behind the magnetizing current I_m, that I_2 lags by a little more than 90° behind Φ, and that the phase difference between E_t and I_m is not exactly 90°, have been purposely disregarded as immaterial in connection with the points under investigation in this paper.

If it be desired to reproduce the exact operating conditions of Fig. 10 when the machine passes from asynchronous to synchronous operation, how is the magnitude of the unidirectional magnetization to be chosen? To answer this question it is necessary to remember that so long as the terminal voltage remains

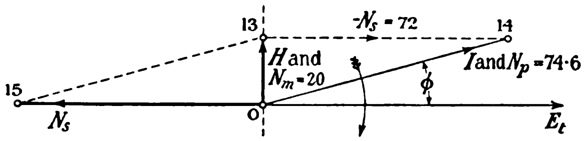

FIG. 11.—Vector diagram of synchronous motor operating at same load and power factor as the asynchronous motor of Fig. 10.

unchanged the magnitude of the resultant motor magnetization must remain the same and retain the same phase relation to that voltage. The resultant magnetization H of the synchronous motor must then be equal in magnitude to and of the same phase as the revolving flux Φ of the asynchronous machine. The primary current I is to remain unaltered and retain the same phase relation to the terminal voltage E_t. The ampere-turns N_p produced by I of the synchronous motor, usually referred to as armature ampere-turns, must therefore be equal to the total primary ampere-turns of the asynchronous machine, and I must lag ϕ degrees behind E_t, as shown in Fig. 11. Now it is known that N_m of the synchronous motor, which determines H, must be the resultant of N_p and N_s, with the result that the unidirectional ampere-turns N_s on the secondary of the synchronous motor must be equal to the ampere-turns produced on the secondary of the asynchronous motor by the secondary load current I_2. The answer to the question propounded at the commencement of this paragraph is therefore: In order to duplicate the asynchronous performance characterized by Fig. 10 after the motor has stepped into synchronism, it is necessary to make the unidirectional ampere-turns of the synchronous motor (usually but inaccurately referred to as " exciting ampere-turns") equal to the secondary load ampere-turns of the asynchronous motor of Fig. 10.

Holding to the simplifying assumptions on which Fig. 10 is based, a few simple relations can be stated, to throw further light on the true functions and magnitude of the unidirectional ampere-turns on the secondary of a synchronous motor. A clear conception of the design limitations, particularly in respect to conversion and weight efficiency of synchronous induction motors, cannot be had without a full comprehension of the true significance of these unidirectional ampere-turns.

In both motors the torque is proportional to that component of the secondary ampere-turns (vector 0–15 in Figs. 10 and 11) which is at right angles to the motor magnetization Φ or H. In the asynchronous machine the phase of this vector changes but little when the load varies from zero to the guaranteed overload, slowly increasing its lag behind Φ. This change in phase is brought about by an increasingly great and permanent departure from the synchronous speed. Its magnitude is determined by the time constant of the secondary. In the synchronous motor this vector may travel through about 90° within the same load limits, its change in phase, really in space position, being brought about by accelerations or decelerations of the revolving member of extremely short duration, in fact by momentary departures from synchronism. With constant unidirectional ampere-turns on the secondary an increase in load increases the lag of N_s behind H.

For a given number of unidirectional ampere-turns N_s on the secondary of a synchronous motor the maximum synchronous torque is available when N_s is at right angles to H, as in Fig. 11. When this occurs I lags behind E_t and $\tan\phi = N_m/N_s$. All of the resultant motor magnetization is supplied by the primary; the secondary carries nothing but load ampere-turns, and N_s is equal to the total load ampere-turns of the motor. Fig. 11 illustrates this limiting case for the synchronous machine. An increase in torque demand causes the motor to lapse into asynchronism, unless N_s is simultaneously increased to a sufficient extent, and this for the reason that for a given value of N_s its projection on the perpendicular to H is a maximum when N_s is itself perpendicular to H.

The unidirectional ampere-turns on the secondary of a synchronous motor are sometimes spoken of as ampere-turns which neutralize the primary working ampere-turns. The author has often followed this practice, but it is thought that it is distinctly misleading. The unidirectional ampere-turns on the secondary of a synchronous motor are the true load ampere-turns on the machine, for they are in the same direction as the load ampere-turns on the secondary of an asynchronous motor,

and replace these when the motor steps from asynchronous to synchronous operation. All or part of these secondary ampere-turns are, as a matter of fact, neutralized by the primary ampere-turns.

When $N_p = N_s$, as in Fig. 12, one half of the resultant motor magnetization H is supplied by N_s, the other half by N_p. The primary current still lags behind the terminal voltage, and the phase angle is given by $\sin\phi = \frac{1}{2} N_m / N_s$.

When the power factor is unity, $N_s = \sqrt{[N_p^2 + N_m^2]}$ and all the resultant motor magnetization is supplied by the unidirectional ampere-turns on the secondary (see Fig. 13).

Even if an automatic regulator is used to control the ampere-turns in the secondary circuit of a syn-

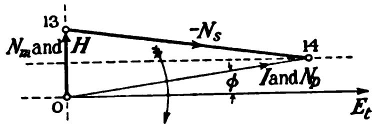

FIG. 12.—Vector diagram of synchronous motor when primary and secondary ampere-turns are equal.

chronous induction motor so as to keep the power factor at unity as long as possible, these ampere-turns will be in excess of the necessary working ampere-turns right down to the point of maximum synchronous torque. Except near the breakdown point they will be equal to the vectorial sum of load and exciting ampere-turns. Any designer, wishing to keep the conversion and weight efficiencies of a polyphase synchronous induction motor operating as a synchronous machine the same as the conversion and weight efficiencies of a corresponding polyphase asynchronous motor, is faced with the very serious difficulty of so distributing the available secondary copper in the secondary windings that they will be capable of carrying, without increased losses or

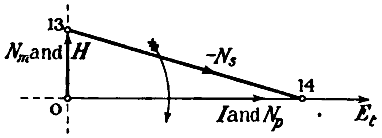

FIG. 13.—Vector diagram of synchronous motor when power factor is unity.

heating, polyphase load ampere-turns for the non-synchronous, and unidirectional load and exciting ampere-turns for the synchronous, operation. The difficulty is enhanced by the facts that the unidirectional ampere-turns must be carried in a single-phase winding, i.e. one having but one axis per pole-pair, that these ampere-turns very greatly exceed the corresponding polyphase ampere-turns at all loads other than the maximum synchronous load, and that the polyphase ampere-turns must be carried in a polyphase winding. This polyphase winding cannot be discarded because it is needed at starting.

It is quite true that the whole or any part of the polyphase winding is available for carrying the unidirectional ampere-turns in synchronous operation, but this relief, whilst most welcome, is not as far-reaching as might at first appear. The reason is that, in practice, a part only of the polyphase winding can be used to carry the unidirectional ampere-turns in synchronous operation. A given number of ampere-turns will produce the maximum number of magnetic lines when the winding is a concentrated one, each turn embracing all the pole area. Distributing the same number of turns over the whole pole requires just twice the number of ampere-turns to produce the same flux. Since, for a given amount of copper, the losses increase with the square of the ampere-turns, it is clear that, in so far as losses are concerned, the concentrated winding is by far the most advantageous, but its cooling facilities are the poorest and its leakage coefficient a maximum. A compromise is clearly indicated. The best that can be done in practice is to use one phase of a two-phase secondary winding, or one or two phases of a three-phase secondary winding, to carry the unidirectional ampere-turns in synchronous operation.

These brief considerations make it quite evident that if the weight of copper on the secondary is not increased the conversion efficiency must suffer, as the increased heating necessitates a reduction in output, and this means that less money can be collected by the maker for the same amount of material. If the weight of copper is increased it necessitates an increase in other material, and means the same amount of money collected for a machine requiring more material.

The author's suggestion is therefore to use practically the same amount of material and thereby limit the maximum synchronous load, but otherwise so to design the machine as to make it possible for it to meet overloads asynchronously. In this way it becomes possible to utilize part of the material on the secondary to the best advantage from the point of view of power factor during normal operation, and to utilize all of this material to the best advantage from the weight-efficiency standpoint during the overload periods.

After this discussion it will be easy to select a reasonable ratio of $N_{s.\,max.}/N_m$ as a basis of comparison for synchronous performances. Suppose that the magnetizing current of a polyphase induction motor is 20 amperes per phase, while its full-load current is 54 amperes with a torque component of 48 amperes; then a synchronous motor built into the frame of this induction motor will show a 50 per cent overload capacity if the ratio of its maximum unidirectional ampere-turns on the secondary, $N_{s.\,max.}$, to the constant ampere-turns, N_m, required for producing H, is as 72 to 20. This is the conservative ratio used hereafter. Fig. 11 applies to a machine embodying this ratio, and shows its theoretical breakdown point or point of maximum synchronous torque.

Turning back to Fig. 2, its inherent *synchronous* performance characteristic with B on open circuit, i.e. when in the form of the motor of Fig. 14, can be rapidly analysed by means of a circle diagram. The machine is self-excited and the exciting voltage e_1 depends on rotor speed, magnitude of H, and angular relation α of axis of H (or of Φ) to the axis of the brushes 9, 10. Speed is synchronous and therefore constant, and, as a first approximation, H may be assumed constant, which makes e_1 proportional to $\sin\alpha$. But e_1 determines the magnitude of N_s for a given number of turns in A and a given

resistance of the circuit comprising A and the brushes 9, 10; consequently N_s is proportional to sin α. The maximum of N_s and the value of H are known; it is also known that sin α, and therefore N_s, are a maximum when H is at right angles to the axis of the brushes 9, 10. In addition, H lags 90° behind the terminal voltage E_t and is always due to the resultant of N_s and N_p. The angular relation c between H and N_s is zero at no load, and 90° at full load. In the case of Fig. 14 the axis of N_s, which must coincide with that of A, coincides with the brush axis, and $c = \alpha$. To acquire information as

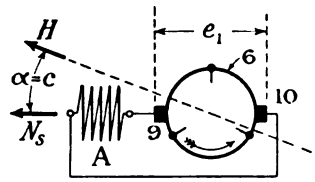

FIG. 14.—Self-excited synchronous induction motor with brush axis coinciding with axis of secondary winding to which brushes are connected (Fynn form 1).

to the conditions under different loads, one may imagine H and E_t stationary in space and displace the brush axis together with the axis of N_s, or vice versa. The former plan is selected because it is more convenient.

In Fig. 15, which is to scale, H is 20 and at right angles to E_t. On the rearward prolongation of E_t the distance 0–16 represents the maximum value of N_s, which is 72. This value of N_s is reached when $\alpha = 90$, and the axis of the brushes 9, 10, therefore coincides with 0–16; at this time I equals 16–13. For the value of α specifically shown in Fig. 15, the value of N_s is 0–15 and that of I is 15–13. The locus for the end of the vector N_s

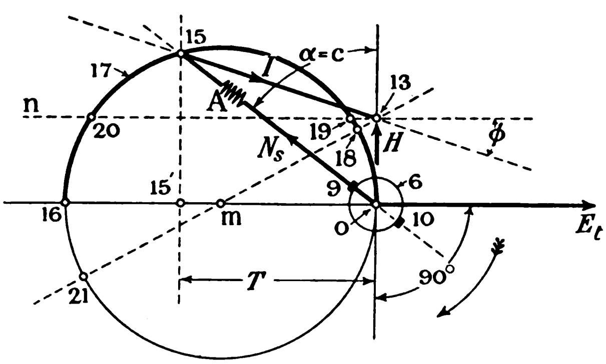

FIG. 15.—Circle diagram for self-excited synchronous induction motor of Fig. 14 running synchronously.

is the circle 17 drawn about the half-way point (m) on the line 0–16 with a radius equal to $\frac{1}{2}N_s$. The torque for any value of N_s is proportional to the projection of N_s on the perpendicular to H. Thus when N_s equals 0–15 the torque is proportional to 0–15′. The direction of the torque is determined by the relative directions of H and of the projection of N_s on the perpendicular to H. The primary current is proportional to the vector 15–13, and the phase angle ϕ between the terminal voltage and primary current is the angle between 15–13 and OE_t or n, where n is a parallel to OE_t drawn through the end 13 of the vector H. The speed is constant.

At no load, H coincides with N_s. In Fig. 15 the brush axis, that of A, and that of N_s are then vertical, $c=0$, $\alpha = 0$, $N_s = 0$, $I = H$, and $\phi = 90°$ lagging. As α increases, I decreases and reaches a minimum when N_s equals 0–18, at which point I is coaxial with a diameter of the locus 17. Thereafter I increases to a maximum, which is reached when N_s equals 0–21. This occurs after α has travelled through an additional 90°. When $\alpha = 180°$ the current I is again equal to H. The phase angle ϕ diminishes very rapidly at first as α increases, and becomes zero, which corresponds to unity power factor, when N_s equals 0–19. Thereafter α becomes positive or leading, reaches a positive maximum when I is tangential to the locus 17, and is back at zero when N_s equals 0–20. For greater values of α the angle ϕ is

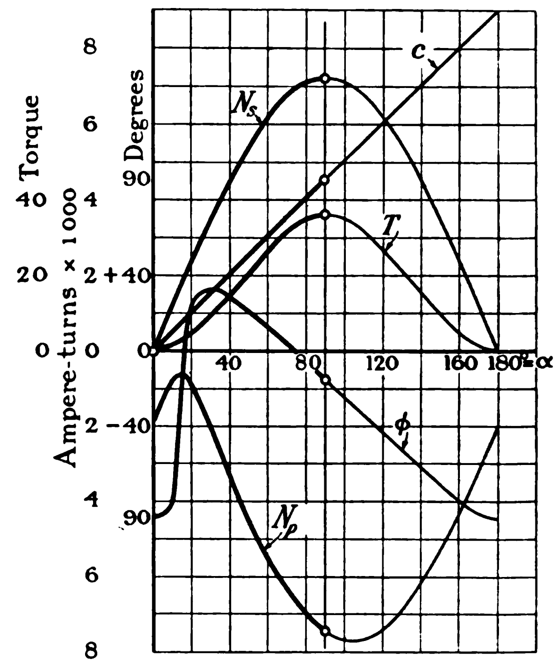

FIG. 16.—Synchronous performance curves of self-excited synchronous induction motor of Fig. 14.

negative or lagging, and goes back to 90° lagging when $\alpha = 180°$. The angle c increases steadily with α. As soon as α exceeds 180° the polarity of e_1, and therefore of N_s, reverses. If the machine synchronizes for any value of α between 0° and 90° when Φ is positive, it will synchronize for any value of α between 180° and 270° when Φ is negative, otherwise the performance is identical and the diagram of Fig. 15 holds for either polarity.

Fig. 16 shows the synchronous performance curves of the motor of Fig. 2 with B circuit open, or of that of Fig. 14, as calculated from the circle diagram Fig. 15. These curves are plotted against α on the basis of the arbitrary assumption made in connection with Fig. 2, that from right to left and from top to bottom are positive. Positive values are plotted above, negative values below, the horizontal.

The torque curve T at once indicates that conditions

become unstable for values of c in excess of 90°. Since c *increases* with increased demand for torque, the motor must break down when c exceeds 90°, for beyond that point the torque diminishes with increasing c. The useful portions of the performance curves of Fig. 16 and of the locus for N_s in Fig. 15 are shown by heavy lines.

The motor of Fig. 14 will operate synchronously from zero to maximum torque and may synchronize on either polarity of Φ. If it synchronizes when Φ is positive it will be because N_s is positive at the time, and the

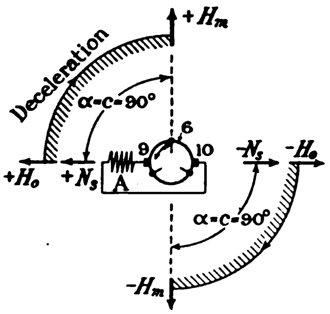

FIG. 17.—Showing synchronous angular relations under varying load of secondary ampere-turns N_s and resultant motor magnetization H for the two possible secondary polarities of motor of Fig. 14.

resultant motor magnetization H will oscillate between position ($+H_0$) for zero torque and position ($+H_m$) for maximum torque, as shown in Fig. 17. If it synchronizes when Φ is negative, H will oscillate between ($-H_0$) and ($-H_m$). In Fig. 17 the primary revolves counter-clockwise; it accelerates upon a reduction of load and decelerates upon an increase in load.

The synchronous performance of the motor of Fig. 14 is not very desirable from the power-factor point of view and the machine is very unstable at fractional loads,

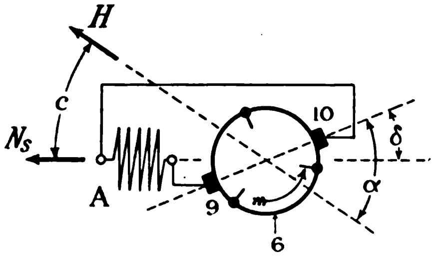

FIG. 18.—Self-excited synchronous induction motor with brush axis displaced from axis of secondary winding to which brushes are connected (Fynn form 1).

a slight change in load at light loads or a small displacement of the brushes, such as may be due to wear, causing wide variations in line current and power factor. In short, the compounding characteristic of this machine is not satisfactory. This can be very simply remedied by displacing the brush axis from that of the secondary winding A, or vice versa. Let the brushes be displaced from the axis of A in the direction of rotation of the primary and by $\delta = 22{\cdot}5°$, as shown in Fig. 18. This angle is chosen because it is a convenient fraction of 90, but any angle of about this magnitude gives good results.

The circle diagram for Fig. 18 is shown in Fig. 19. Let the line 0–16 represent the maximum value of N_s and equal 72. Halve 0–16 and describe the circle 17 about its middle point (m) with a radius $\frac{1}{2}N_s$. When the axis of A coincides with 0–16, that of N_s must also coincide with it. N_s is a maximum when H is at right angles to the brush axis, but according to Fig. 18 the brush axis is displaced by δ degrees from the axis of A against the (in this case) clockwise direction of rotation of the revolving flux set up by the primary. This means that for $N_{s.max.}$ the resultant H must be displaced in like manner from the perpendicular to $N_{s.max.}$. In Fig. 19, H is therefore inclined by $(90 - \delta)$ with respect to the line 0–16 representing $N_{s.max.}$. This fixes the location of E_t, which must be at right angles to and must lead H. The circle 17 is again the locus for N_s.

Fig. 20 shows the performance curves calculated from Fig. 19 and plotted against α. It is to be noted that in Fig. 19 the angles c and α differ by the constant angle δ. For $\alpha = 0$, $N_s = 0$ and the primary current I equals

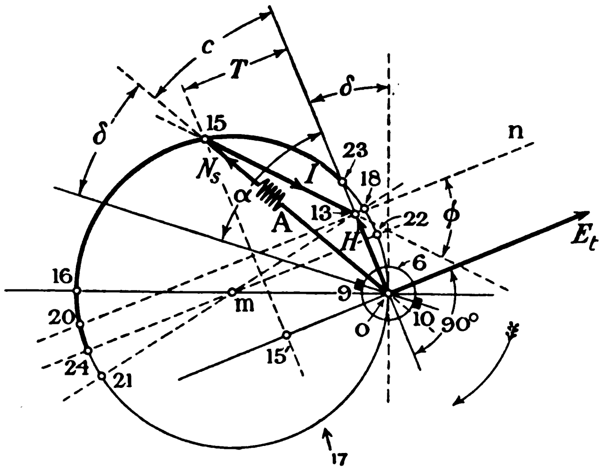

FIG. 19.—Circle diagram for self-excited synchronous induction motor of Fig. 18 running synchronously.

N_m or H. As α increases, I diminishes until N_s equals 0–18. This is one intersection with the locus of that diameter of 17 which passes through 13. Beyond this point I increases, reaching a maximum when N_s equals 0–21, the point 21 being the other intersection of the diameter just referred to with the locus 17. Thereafter I diminishes, becoming again equal to H for $\alpha = 180$. The phase angle ϕ is negative and lags 90° for $\alpha = 0$, increases to 180° lag (or lead) when N_s equals 0–19, decreases to 90° lead when N_s equals 0–23 and to zero when N_s equals 0–20, thereafter gradually increasing back to a 90° lag. Points 19 and 20 are the intersections of n, a parallel to E_t through 13, with the locus 17. The point 19 is not shown because it falls very close to point 18.

Zero torque occurs for $\alpha = 0$ because N_s is then zero, and also for $\alpha = 22{\cdot}5°$ because the axis of A then coincides with that of H. Between these two values of α the torque is negative. As α passes the value of δ the projection of N_s on the perpendicular to H changes sign and the motor torque becomes positive. The maximum positive and negative torques are determined by the two

intersections of the locus 17 with a parallel to E_t drawn through m. Point 24 fixes the value of the maximum positive torque and point 22 that of the maximum negative torque.

The useful parts of the performance curves of Fig. 20 and of the locus for N_s of Fig. 19 are shown in heavy line in these figures.

Fig. 21 corresponds to Fig. 17 and indicates, for either polarity, how H varies in relation to the brush axis and to that of A when the synchronous torque varies from zero to its maximum. It is seen that the range of c is reduced from 90° to 78·75° as compared with Fig. 17; $c = 90 - \frac{1}{2}\delta$.

The maximum constant synchronizing torque is secured when each brush set is coaxial with the secondary

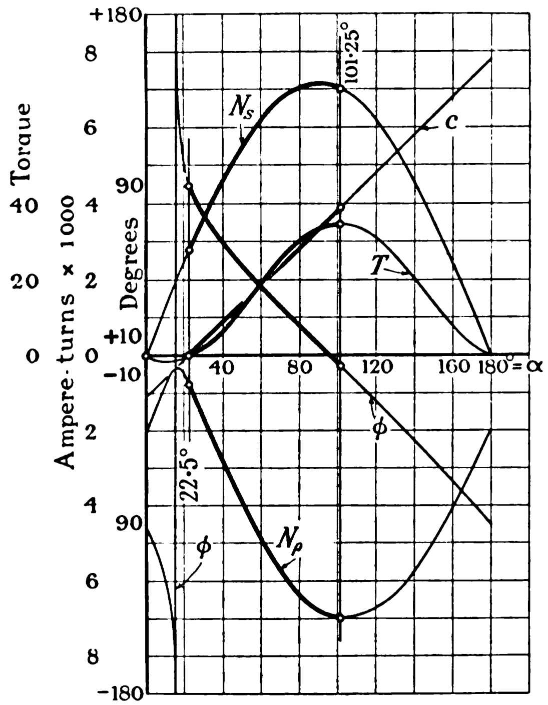

FIG. 20.—Synchronous performance curves of self-excited synchronous induction motor of Fig. 18.

winding to which it is connected, as shown in Fig. 2. One way to secure synchronous operation and a compounding characteristic is to open the circuit of one of the secondary windings upon synchronism being reached. One method of securing a more generally useful compounding characteristic is to open the circuit of one of the secondary windings and to displace the brushes of the other set by a small angle δ. From a practical standpoint brush-shifting is not desirable in connection with general-purpose motors, and the question arises how and to what extent the starting and synchronizing performances will be affected if one or both brush sets are permanently displaced by that small angle δ which yields the desired compounding characteristic. Also, just how do the inclusion of the brush voltages in the secondary circuits and the contemplated brush displacements affect the starting performance of the machine?

Let us answer the last question first. The amplitude of the brush voltages is constant at all motor speeds, and is small as compared with that of the voltages generated in the secondaries A and B by the revolving flux Φ when the rotor speed is zero. For this reason the influence of the brush voltages on the static torque is not very great. When the axis of a brush set coincides with the axis of the secondary to which the brush set is connected to produce a positive synchronizing torque, the brush voltage is in phase with that generated in the secondary and increases the starting current and the starting torque but does not affect the starting torque per ampere. When the axis of a brush set is displaced from the axis of the secondary to which the brush set is connected, the voltage at the brushes may lead the voltage generated in the secondary or may lag behind it. In either case it increases the starting current and affects the starting torque per ampere. A leading brush voltage increases the static torque per ampere by decreasing the lag of the secondary current, whilst a lagging brush voltage increases the lag and reduces the torque per ampere at starting.

The displacement of the brush axis shown in Fig. 18 results in a leading brush voltage. If one set of brushes

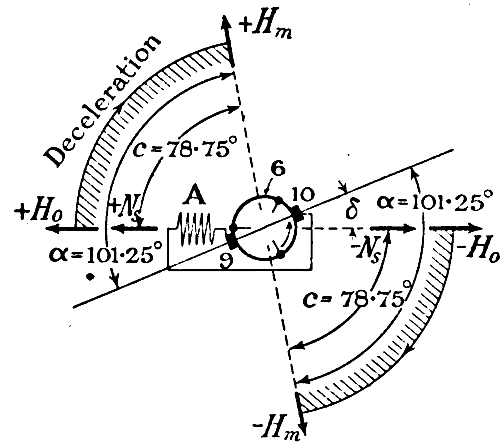

FIG. 21.—Showing synchronous angular relations under varying load of secondary ampere-turns N_s and resultant motor magnetization H for the two possible secondary polarities of motor of Fig. 18.

is displaced as in Fig. 18 and the other is left coaxial with the secondary to which it is connected, then the conditions at starting will be somewhat unbalanced. Whilst this difference is not at all serious for small values of δ, yet in so far as starting performance is concerned it is better, if a displacement is called for, to displace both brush sets to the same extent and in the same direction.

The effect of brush displacements on the synchronizing torque is of greater interest. When the axis of a brush set coincides with the axis of the secondary to which it is connected, the synchronizing torque produced by that particular secondary is strictly unidirectional, as in Figs. 5 and 7, and its amplitude is proportional to the maximum ampere-turns in that secondary. For the winding A the maxima occur for $\alpha = c = 90°$ and for $\alpha = c = 270°$. When one set of brushes is displaced by δ degrees as in Fig, 18, the synchronizing torque produced

by the secondary winding connected to it becomes alternating, with unequal positive and negative maxima. As δ increases, the negative maxima increase and the positive ones decrease; for $\delta = 90°$ all maxima are of equal amplitude, and the synchronizing torque is a purely alternating one. For any value of δ the negative maximum d_1 is proportional to $\sin^2 \frac{1}{2}\delta$, and the positive maximum d_2 is proportional to $\sin^2 \frac{1}{2}(180 - \delta)$. It is

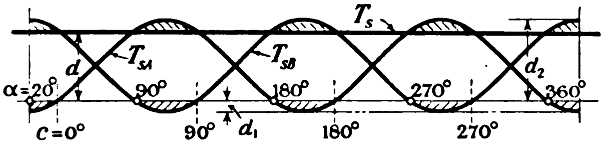

FIG. 22.—Showing resultant constant synchronizing torque when axes of polyphase arrangement of brushes on the primary are displaced from the axes of polyphase arrangement of windings on the secondary to which the brushes are connected.

important to note that when δ differs from zero the positive maxima occur for values of c which differ from those at which the maxima occur when $\delta = 0$. When δ differs from zero, $c = a - \delta$. It is seen that if only one set of brushes of Fig. 2 is displaced the synchronizing torque must be the resultant of a strictly unidirectional torque and of an alternating torque with unequal maxima. In addition, the positive maxima of these torques are displaced by more or less than 90°. The

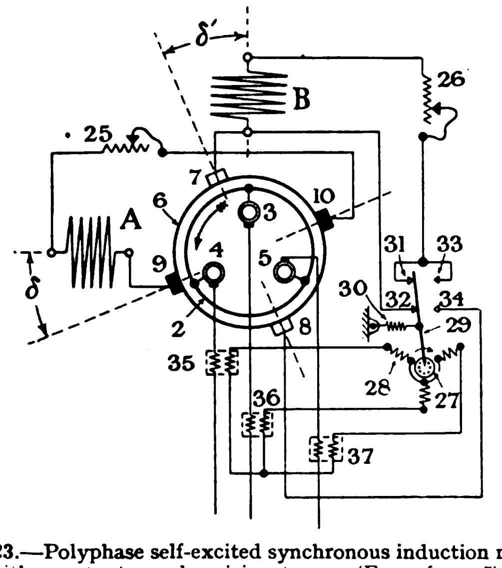

FIG. 23.—Polyphase self-excited synchronous induction motor with constant synchronizing torque (Fynn form 5).

resultant torque cannot be constant, but is very nearly so for small values of δ.

If, in Fig. 2, the brushes 9, 10 are displaced by 22·5° from A and the brushes 7, 8 are left coaxial with B, the synchronizing torque conditions change as follows:—B produces a unidirectional torque as before, its maximum being proportional to $N_{B\,max.} \sin^2 90$ or, say, to unity. A now produces an alternating torque, its maximum positive value proportional to $N_{A\,max.} \sin^2 78 \cdot 75$, or to 0·961, and its maximum negative amplitude to $N_{A\,max.} \sin^2 11 \cdot 25$, or to 0·039. In addition, the angular displacement of the positive maximum of the torque due to A from the maximum of the torque due to B is not 90° as before the brushes 9, 10, were displaced, but $90° \pm 11 \cdot 25°$ according to the direction in which the brushes 9, 10, have been moved.

If both brush sets of Fig. 2 are displaced in the same direction and by the same angle δ, then the resultant synchronizing torque remains absolutely constant but diminishes with increasing δ, becoming zero for $\delta = 90°$. As δ increases, the positive and negative maxima vary as stated in the preceding paragraph, but the angular displacement of the maxima of the component torques remains constant and equal in magnitude to the angular displacement of the two sets of brushes. This case is illustrated in Fig. 22. The amplitude d of the resultant synchronizing torque T_s is equal to the difference $(d_2 - d_1)$ of positive and negative amplitudes of the component torques. For $\delta = 22 \cdot 5$, $d_1 = 0 \cdot 039$ and $d_2 = 0 \cdot 961$, provided $N_{A\,max.} = N_{B\,max.}$ as is here

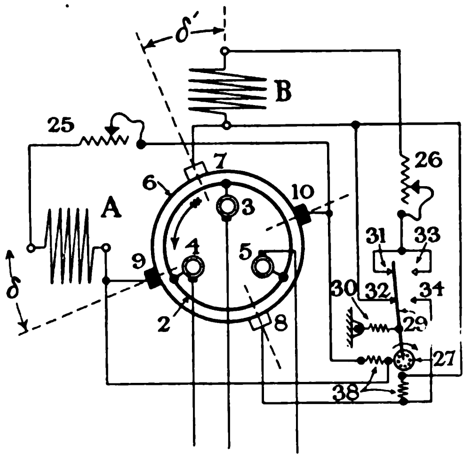

FIG. 24.—Polyphase self-excited synchronous induction motor with constant synchronizing torque (Fynn form 5).

assumed. Under these conditions $d = 0 \cdot 922$, which means that T_s is only 7·8 per cent less than for $\delta = 0$.

On the whole it is therefore preferable, for the sake of the starting as well as for the sake of the synchronizing performance, to displace both brush sets by that angle δ which corresponds to the desired compounding characteristic, and it is desirable from every viewpoint to keep δ small. Values around 20° give very good results. The author's polyphase synchronous induction motors of form 5 have been constructed on these very lines, and three self-excited examples of this form are shown diagrammatically in Figs. 23, 24 and 25.

Referring to Fig. 23, the rotor is the primary and carries a winding 2 adapted for connection to the supply through the slip-rings 3, 4, 5, and a commuted winding 6 with which co-operate the two brush sets 7, 8, and 9, 10. The stator, here the secondary, carries the windings A and B. The brushes 9, 10, are displaced by δ degrees from the axis of A, the brushes 7, 8, by δ' degrees from the axis of B. The brush axes are displaced in the direction of rotation of the primary and against the direction of rotation of the revolving flux Φ set up by

the primary at starting. In this example $\delta = \delta'$; this equality is preferable but not necessary. The secondary A is permanently connected to the brushes 9, 10, with the interposition of the adjustable resistance 25. The circuit of the secondary B includes the adjustable resistance 26, and is under the control of the relay or switch 27, 28, 29. Normally the relay blade 29 is under the control of the spring 30, and B is short-circuited or closed over any part of 26 at the contacts 31, 32. In the other position of this blade 29 it bridges contacts 33, 34, and this connects B to the brushes 7, 8, with the interposition of 26. The relay consists of a rotor 27 carrying the blade 29 and provided with a squirrel-cage winding, and of a stator carrying the three-phase winding 28 connected to the secondaries of the three star-connected series transformers 35, 36, 37, the primaries of which are in series with the slip-rings of the motor and carry line currents. The connections between these transformers and the relay are made to produce a clockwise torque in the rotor 27, tending to overpower the spring 30.

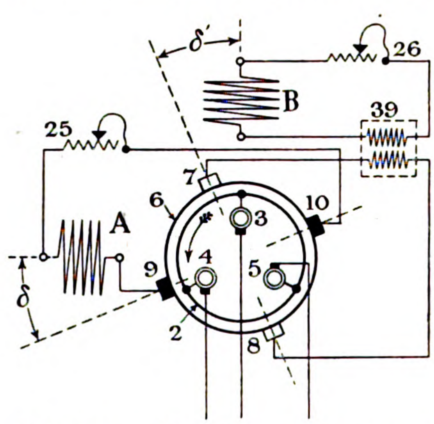

FIG. 25.—Polyphase self-excited synchronous induction motor with constant synchronizing torque (Fynn form 5).

The magnitude of this torque increases with increasing line currents, and the adjustments are so made that when the line current exceeds that value which corresponds to the maximum synchronous torque, the blade 29 moves to bridge the contacts 33 and 34.

The operation of this new machine is as follows. So long as the starting current does not exceed that which corresponds to the maximum synchronous torque, the connections remain as shown in Fig. 23, the value of the starting torque being determined by the terminal voltage and the magnitude of the resistances included in the circuits of A and of B. The synchronizing torque is alternating but with very unequal positive and negative maxima and is, in fact, substantially unidirectional. It is equal to the maximum synchronous torque when 25 is set to its synchronous or normal operating value. The machine steps into synchronism very smoothly and operates synchronously for any torque demand from zero up to and including a value equal to the maximum synchronous torque. The compounding characteristic depends on the value of δ.

For $\delta = 22 \cdot 5°$ the compounding characteristic is that shown in Fig. 20; when 25 is set to its normal operating value the synchronizing torque is $N_{A\,max.} \sin^2 78 \cdot 75 = 0 \cdot 961$ and the maximum synchonous torque is of identical magnitude.

When the torque demand exceeds the maximum synchronous torque, the motor slips out of synchronism and the secondary B is simultaneously connected to the brushes 7, 8. Because of this automatic connection of B to 7, 8, the synchronizing torque which appears when an overload forces the motor into asynchronism is absolutely constant instead of being pulsating, as is the case when the secondary A is alone connected to a brush voltage.

For $\delta = 22 \cdot 5°$ the value of this constant synchronizing torque is proportional to $0 \cdot 922$, as explained in connection with Fig. 22, and therefore only 4 per cent less than the maximum synchronous torque which corresponds to the same value of δ. The result is that the transition from synchronous to asynchronous operation cannot be detected without reference to the ammeter and wattmeter. Detection is all the more difficult since the theoretical maximum synchronous torque is never reached, because of the primary impedance, whereas the theoretical synchronizing torque is much more closely approached.

The action of the relay is very positive because of the sharp rise in line current which occurs at the time the maximum synchronous torque is very closely approached. This sharp rise is well shown by the performance curves of Fig. 1.

With this constant synchronizing torque the motor speed under overloads is quite as smooth as that of any asynchronous motor, and such a machine is suitable for any service capable of being handled by the ordinary non-synchronous motor.

The new motor of Fig. 24 differs from that of Fig. 23 in that the relay controlling the circuit of the second secondary winding B is wound for connection to the brush voltages instead of being made responsive to changes in the line currents. To this end the stator of the relay is provided with a two-phase winding 38, one phase of which is connected to the brushes 7, 8, and the other to the brushes 9, 10. The operation of this motor differs somewhat from that of Fig. 23. Here the torque of the relay depends on the nature of the brush voltage. So long as the brush voltage is alternating, the rotor 27 exerts a clockwise torque tending to bridge contacts 33, 34, and thus connect B to brushes 7, 8. As soon as the brush voltage becomes unidirectional, in other words, instantly upon synchronism being reached, the relay torque becomes zero and spring 30 is left in undisputed control of the blade 29. Since the amplitude of the brush voltage is independent of speed and depends only on the magnitude of Φ, the relay torque increases with decreasing brush-voltage frequency. According to the manner in which the design constants of the relay are chosen, the blade 29 may connect winding B to the brushes 7, 8, at the moment of connecting the motor to the line or at some sub-synchronous speed during the period of acceleration, but in any case the contacts 33 and 34 are bridged at the very instant the maximum synchronous torque is exceeded and the brush voltages become alternating owing to the lapse of the machine into asynchronism because of an overload. At such

time the current in the relay windings 38 is a maximum and the relay torque a maximum.

The novel arrangement shown in Fig. 25 is perhaps the most interesting. Here the secondary A is in *conductive* connection with the brushes 9, 10, as before, but the connection between the secondary B and the brushes 7, 8, is *inductive*, being accomplished by means of the static transformer 39, one winding of which is connected to the brushes 7, 8, whilst the other is connected to the secondary winding B. At synchronism the inductive connection between B and the brushes 7, 8, is quite inactive, because the brush voltages are unidirectional, and the compounding characteristic of the motor is determined by the secondary A and the angle δ in accordance with a circle diagram such as that of Fig 19. Upon departure from synchronism, no matter how small that departure may be, the inductive connection between 3 and the brushes 7, 8, becomes active and the machine exhibits a constant synchronizing torque such as is obtained in Figs. 23 and 24 when the blade 29 of the relay bridges the contacts 33, 34.

The motors shown in Figs. 23, 24 and 25 start with a higher torque per ampere than the ordinary asynchronous motor, operate synchronously and with high power factor on all normal loads from zero to a little beyond full load, and operate non-synchronously on all overloads, but without the least irregularity of speed or any kind of periodic variation or oscillation of the peripheral velocity of the revolving member. As a result, the weight efficiency of these machines is considerably greater than that of any other synchronous induction motors, and their range of utility is also much greater.

Whilst the motors specifically described have revolving primaries, identical results are obtained by placing the primary on the stationary member and revolving the brushes with the rotor. The several means shown and described for rendering the second component of the synchronizing torque effective at the proper time are applicable to separately excited * as well as to self-excited synchronous induction motors.

* See paper entitled "A New Separately Excited Synchronous Induction Motor," *Engineering*, 1925, vol. 119, pp. 215, 281 and 343.

NOTES ON THE CONSTRUCTION OF HEATING AND COOKING UTENSILS.*

By Professor H. BOHLE, Member.

(*Paper first received* 19*th February, and in final form* 14*th December,* 1925.)

SUMMARY.

The paper deals with temperature tests and life tests on heating-wires for electrical heating and cooking utensils and with tests on hot-plates, and describes new types of elements and utensils.

(1) GENERAL.

It is a somewhat remarkable fact that after nearly half a century of electrical engineering the use of electricity for general domestic purposes is still the exception and not the rule. With the exception of the people in the larger towns of North America, probably not even 5 per cent of the public employ electrical appliances throughout their homes, in spite of the many advantages which the use of electricity offers. The reasons are, however, not far to seek. Whereas the generation and distribution of electricity are in the hands of the few who have concentrated their forces, the application for domestic purposes is in the hands of the multitude, the inexperienced, with the result that most mental energy has been expended on the perfecting of generation and distribution. The super-power station of to-day generates from the same amount of coal more than three times the amount of energy that the smaller station did 25 years ago. Even the heat produced by the generators is now usefully included in the complete heat-cycle of a modern station.

In some countries, such as Great Britain, the gas industry has an enormous hold on the country, and English people are very conservative. There are, however, further reasons for the lack of progress in the general domestic use of electrical energy. The apparatus on the market has been by no means very reliable, and, even where energy was cheap, repair bills and the inconvenience connected with frequent repairs have retarded the more general employment of electrical cooking and heating appliances. Moreover, the first cost of electrical appliances is still high, in many cases the efficiencies have been low, and, lastly, the mental inertia of the man in the street is large. It always takes time to persuade people to adopt entirely new methods of working. Yet none of the difficulties enumerated here are such that they cannot be overcome.

In the first place it seems, of course, absurd to change heat into electrical energy and then back again into heat. The advantages of electricity are, however, so manifold that the double conversion is fully justified. They are too well known by the expert to be enumerated here, yet, incidentally, it may be mentioned that in a fully electrically-equipped house the servant question is easily solved. Also, with a reasonable tariff the monthly expenditure for electricity is lower than with other fuels—assuming, of course, that the most up-to-date utensils are employed—and the life of the kitchen staff is very greatly improved. It is to be hoped that in large towns the use of coal for heating and cooking will before long be prohibited, not only from the standpoint of the conservation of fuel resources, but also for the sake of keeping towns free from soot and smoke. How much more agreeable would life be in a city like London if every smoking chimney had disappeared. It is a great pity that even architects are on the whole very backward in this respect and still design houses without making the necessary arrangements for the general application of electricity for domestic purposes. Perhaps the founding of a society on the lines of the Illuminating Engineering Society, which has done so much for improving lighting, would greatly accelerate the hitherto much retarded progress in the universal use of electrical cooking and heating appliances.

(2) PROPERTIES OF RESISTANCE MATERIALS USED FOR HEATING.

Practically all heating and cooking utensils of to-day use elements made of nickel-chromium alloys. It appears, however, that the properties of such conductors are still not fully understood. This is borne out by the regulations which have from time to time been drawn up by various engineering societies for the use of electrically-heated cooking appliances. I refer here especially to the rule published by one society, which states that all cooking utensils should be tested at 40 per cent in excess of the normal watts. No mention of any maximum temperature is made, although this is the main criterion as regards the life of an element. This is fully proved by the tests which the author has carried out during the past two years, the results of which are partly given in the figures below.

It is well known that conductors which are run at a high temperature not only oxidize but apparently also crystallize, and this occurs the more rapidly the higher the working temperature is. Moreover, nichrome alloys do not recuperate after cooling down, and once oxidation and crystallization have been well advanced, the conductor has become useless.

The investigations of the author deal with (1) the mechanical strength of nichrome materials as a function of the temperature, and (2) the mechanical strength at a given temperature as a function of the time of flow of the current.

A number of wires of different makes were tested,

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their composition being as given in Table 1. The different materials are represented by the letters (*a*) to (*e*), which are not their trade terms.

All the wires tested were new. Wires (*b*) and (*c*) were identical; wires (*a*) and (*e*) come from one country, (*b*), (*c*) and (*d*) from another.

TABLE 1.

Composition of Wires Tested.

Material	Nickel	Iron	Chromium	Remainder
	per cent	per cent	per cent	
(*a*)	58·60	27·97	10·97	Insoluble, mainly carbon
(*b*)	62·40	24·53	11·43	Insoluble, mainly carbon
(*c*)	61·70	25·24	11·26	Insoluble, mainly carbon
(*d*)	83·20	2·11	13·84	Insoluble, mainly carbon
(*e*)	57·41	30·00	11·17	Insoluble, mainly carbon

If we compare this table with the results given in Fig. 5 it appears that the material improves as the percentage of nickel increases and that of iron decreases. But the improvement may be mainly due to the increase

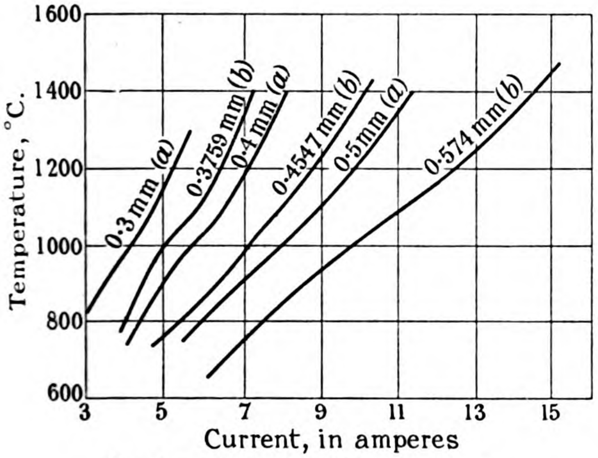

FIG. 1.—Temperature/current curves.

in the percentage of chromium, independently of the percentage of iron. Tests to settle these points are being carried out at present for percentages of chromium up to 35.

Fig. 1 illustrates the temperature/current curves for materials (*a*) and (*b*). The temperatures given are somewhat lower than those stated by the makers for the same currents, probably due to the different methods of suspension employed. The wires under test were stretched between two stout terminals in a rectangular box lined with asbestos (without a lid) in order to prevent the wires being cooled by draughts. The length of each wire was 19·5 cm. If very long wires are used it will be found that at very high temperatures the wire stretches on account of its own weight, so that there is a reduction in the cross-section and a subsequent increase in the temperature for a given current. The temperature was measured when stationary conditions prevailed. The curves show average results, but it should be stated that the test wires were found to be remarkably uniform. The breaking loads in the mechanical-strength/temperature tests never varied by more than ½ lb. This shows that great care is already taken in the manufacture of heating-conductors.

It will be noticed that all the curves in Fig. 1 are S-shaped. This is seen even better by plotting the resistance/temperature curves shown in Fig. 2. The S shape is now clearly defined. It will be obvious from these curves that the calculation of the temperature of

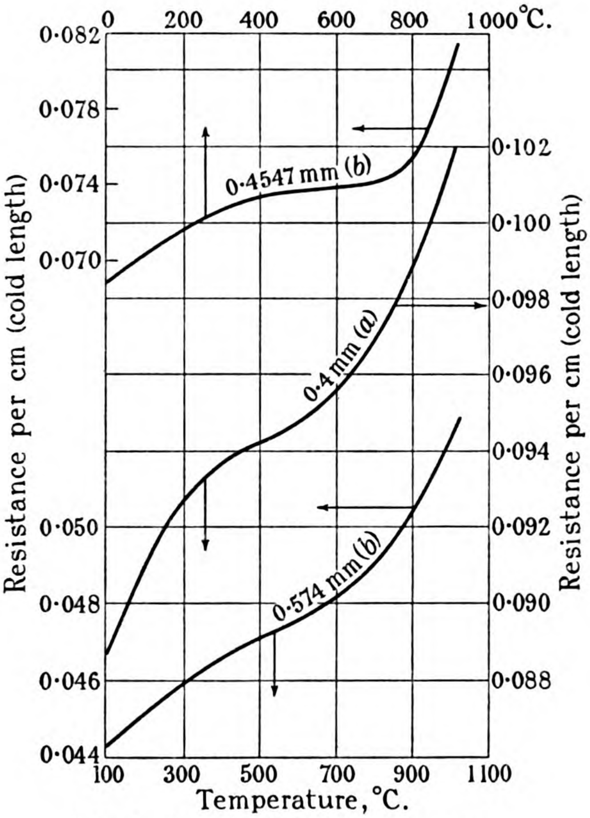

FIG. 2.—Resistance/temperature curves.

heating conductors when employing a constant temperature coefficient will yield unreliable results.

At the lower temperatures the tests were carried out in a Gallenkamp electric furnace with a suitable thermocouple, whereas at the higher temperatures an optical pyrometer was employed.

(3) MECHANICAL STRENGTH.

The mechanical strength of heating-wires as a function of the temperature (or current density) is the most important item from the standpoint of the life of an element. The results are shown in Figs. 3 and 4. The conductors had been subjected to the stated temperatures for 4 hours, and in some cases for 24 hours. It

will be noticed that the additional 20 hours have little effect on the mechanical strength for temperatures up to about 700° C., but beyond this temperature materials (*a*) and (*b*) deteriorate rapidly. This is more clearly shown in Fig. 5. For a working temperature of 700° C., material (*b*) retains its mechanical strength, whereas at 1 000° C. the wire oxidizes very rapidly and loses its

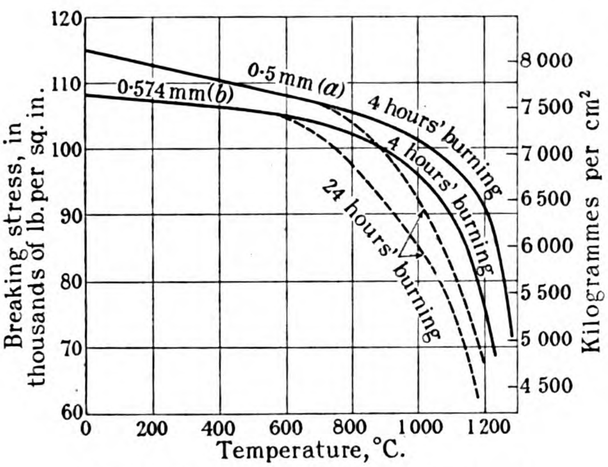

FIG. 3.—Temperature/breaking-stress curves.

mechanical strength. The best material is (*d*), which contains little iron but a large proportion of nickel. Its mechanical strength remains almost constant throughout the life test.

Of interest is the result of the test on material (*e*). This material contains a great deal of iron, yet it does not lose its mechanical strength as much as one would expect. This is due to the fact that the wire is considerably thicker than the others tested, so that proportionally less surface comes into contact with the oxygen of the air.

From the tests it is obvious that the maximum

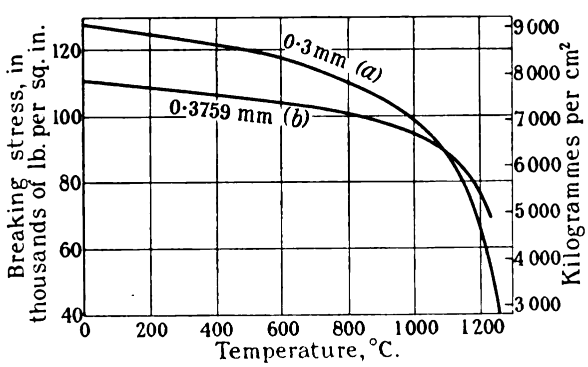

FIG. 4.—Temperature/breaking-stress curves.

temperature of wires (*a*), (*b*), (*c*) and (*e*) should not exceed 700–800° C. unless heavy conductors are used. Material (*d*) can be constantly worked at 1 000° C. This should, however, be the limit, as an increase in the voltage, even if temporary, might do lasting damage to the material. Once nichrome conductors have been subjected to an abnormally high temperature their mechanical strength has disappeared for ever, as there is no recuperation.

The oxidation of heating wires may be prevented by surrounding them with a suitable cement. Such cements should be good insulators, good heat conductors, non-hygroscopic and should not shed water on cooling. The author has been unable to find a cement possessing all these qualities. A special type of alundum was found fairly satisfactory. It has a heat conductivity about

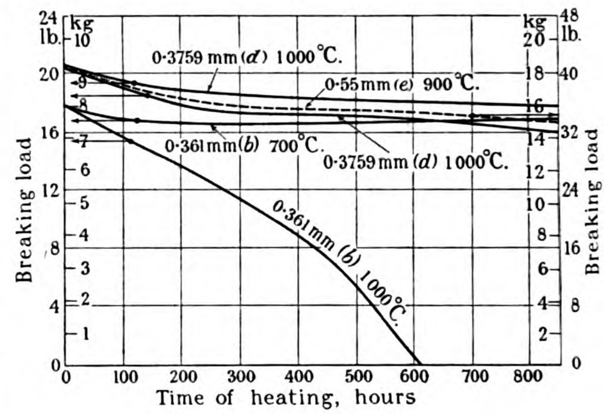

FIG. 5.—Life tests on heating-wires.

3 times greater than that of porcelain; it remains a good insulator even at very high temperatures; it is easily applied, does not crack after drying and does not shed water on cooling. It is, however, somewhat hygroscopic. For water-heating elements which are always in use the cement is excellent.

The mechanical-strength curves have been repeated

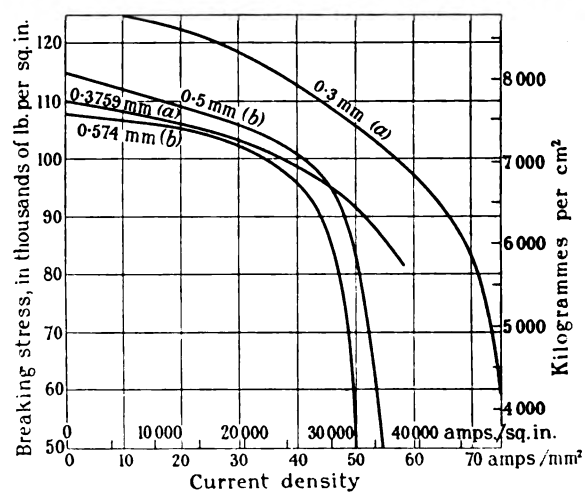

FIG. 6.—Mechanical-strength/current-density curves.

with current densities as abscissæ. The thinner the wire, the greater is the relative radiating surface and consequently the greater is the current density for a given temperature (see Fig. 6).

The fact that crystallization and an alteration in the structure of the wire occurs seems proved by Fig. 7, in which the resistance (after cooling down) has been

plotted as a function of the average temperature of the test, when the heating occurred for 4 hours. It will be seen that the resistance decreases at first until a temperature of about 800° C. is reached, when a rapid increase in the resistance sets in, due to oxidation and crystallization. This temperature should therefore not be materially exceeded.

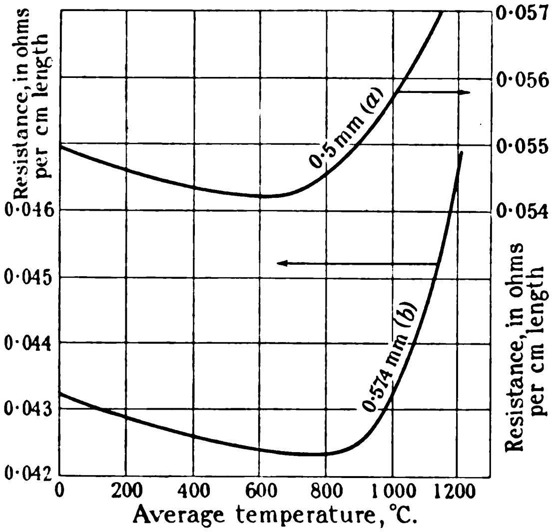

FIG. 7.—Resistance (cold)/temperature curves.

Further interesting results are shown in Fig. 8, which illustrates the change in resistance (hot) as a function of the time. After 40 hours there is an almost instantaneous alteration, but later on the resistance once more increases steadily. Obviously some unstable condition occurs during the life of a heating wire consisting of nichrome.

The conclusions which may be drawn from the results

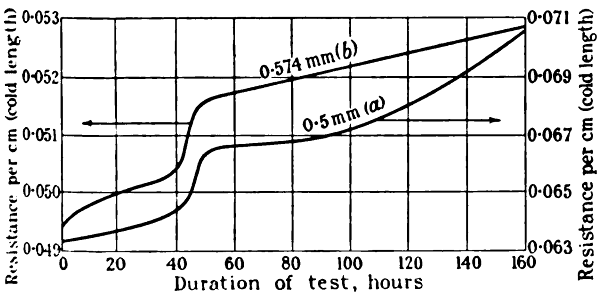

FIG. 8.—Resistance/time curves.

of these tests are obvious. The maximum working temperatures should not exceed values at which the material commences to deteriorate. This temperature should allow for all voltage variations, and in this connection it must not be forgotten that the temperature variation is practically proportional to the square of the voltage variation. To prescribe tests which allow the number of watts to be 40 per cent in excess of the normal, without stating the maximum working temperature, is detrimental to the life of the heating element. It would be far better to give the maximum working temperature, which, however, depends not only upon the current density but also upon the manner of fixing the element and the specific size of the heated surface.

(4) Heating-wires Under Normal Working Conditions.

When a heating element is placed in a cooking utensil, the conditions of working are entirely different from those which obtain when a wire is heated in free air. Radiation has now practically disappeared and is replaced by conduction, and the quality and reliability of a utensil depend mainly upon the quality of the heat conduction. The fall of temperature between the heating wire and the metal surface to be heated is expressed by

$$\theta_r = \frac{\text{watts per cm}^2 \times \text{thickness of insulation}}{\text{heat conductivity of insulation}}$$

This equation tells us that the thickness of the insulating material should be as small as possible and that the heat conductivity of the insulator should be high. The most suitable material is clear mica, not micanite. It withstands great heat, is mechanically strong so that very thin sheets may be used, and it does not fall to pieces when heated to a high temperature. Micanite, which has been frequently employed, always falls to pieces when subjected to great heat; its thickness has to be 3 to 4 times greater than that of pure mica, and its heat conductivity is about 3 times smaller. For a sheet of pure mica 0·025 cm thick the fall of temperature for 1 watt per cm^2 is given by

$$\frac{0 \cdot 025}{3 \cdot 76 \times 10^{-3}} \doteqdot 7 \text{ deg. C.}$$

which is very low. It is, however, essential that no air pockets can form anywhere. Still air is about the best heat insulator which we have, so that the fall of temperature across an air pocket will always be high. The heat conductivity of air, or the amount of heat in watts conducted in 1 second through an area of 1 cm^2 across a gap of 1 cm length for a difference in temperature of 1 degree C., is expressed by $0 \cdot 00022\,(1 + 0 \cdot 00228\theta)$, where $0 \cdot 00022$ is the conductivity at 0° C. and θ is the temperature in degrees C. From this it will be seen that for a gap of only 1 mm length the drop may reach dangerous values. Let us suppose that the average temperature in the gap is 600° C.; then the drop across a 1-mm gap for a specific load of 1 watt per cm^2 is nearly 200 deg. C. With a high loading the melting point of nichrome is soon reached. This shows the danger of loose fitting. In fact, too much emphasis cannot be placed on the necessity of making sure that every inch of the heating wire is firmly pressed against the surface which is to be heated. Moreover, this applies not only to the heating wire proper but also to the connection from the element to the terminals.

The usual practice consists in winding nichrome ribbon around strips of mica. This possesses the disadvantage that the under-surface of the element becomes considerably hotter than the one pressed against the surface to be heated. Moreover, the turns are liable to become short-circuited. To ensure good mechanical

contact with the surface to be heated the element is fixed with a number of screws, which increases the difficulty of replacing an element.

The author has constructed an element, shown in Fig. 9, which has no under-surface. It consists of a sheet of pure mica to which is fixed a helical spiral of nichrome wire. The various convolutions of the spiral are separated from one another by means of magnesia or similar tubes slightly less in diameter than the helix. When now the element is firmly pressed against the bottom of the vessel, which is accomplished by means of a single screw and a suitably sprung steel plate, the helix is reduced to the diameter of the magnesia tubes so that the whole element forms practically a solid plate. This ensures good heat conductivity and the

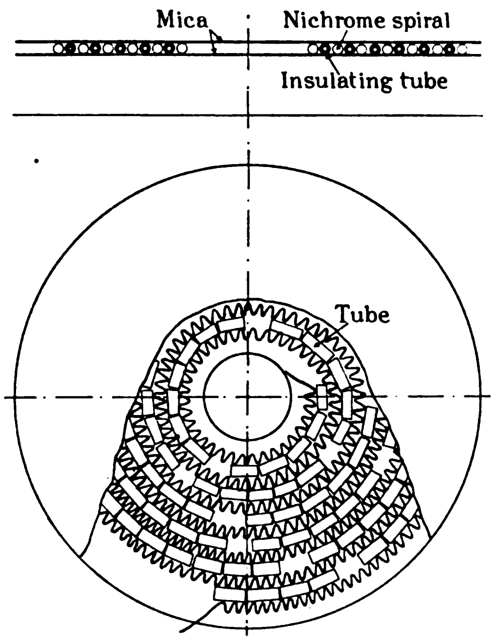

FIG. 9.—Heating element for cooking utensils.

specific load may be as high as 6 watts per cm² without raising the temperature of the heating wire beyond the safe limit.

(5) JOINTS.

It is rarely advisable to join the heating wire directly to the terminals of the utensil. It is frequently mechanically too weak and it may become too hot as well. Whereas the conduction of heat from the element proper may be good, from the connection it may be poor. A larger radiating surface will then be required for the connection, and this can be obtained by joining to the heating wire a stout conductor. A copper flexible cable is unsuitable, as the thin wires soon oxidize and after a short time the flexible cable is burnt through. Even a solid copper conductor does not last long. Constantan, if consisting of fairly thick wires, will give fairly satisfactory results, but pure nickel is best. Care must, however, be taken when making the joint. As only hard soldering can be applied, it may happen that during the heating of the joint the thin heating wire may be raised to a high temperature, somewhat near the melting point, in which case the element would be irreparably damaged before it was completed. Tests were carried out with 24 different types of joints. Copper flexible cables failed after less than 200 hours' burning. Hard sheet brass pressed firmly around heating wire and heavy connecting copper flexible cables gave satisfactory results, so long as the flexible did not become hotter than about 200° C. A very good joint is formed by making the heating wire long enough to be made in a 3-wire strand, the wires being firmly twisted together, the flexible cable thus formed reaching into the heating spiral. Whenever a hard soldered joint is employed, the joint must be well fixed mechanically so that vibration is avoided and the heat can get away. The connection from the element to the terminals may be insulated by means of glass beads if the temperature is not very high, or with a porcelain or silica tube.

On the whole it must be stated that the joints are the weakest parts in an element. On a 220-volt circuit the thickness of the wire rarely exceeds ½ mm, and if strip be used it is very much thinner still. To join heavy conductors to such thin wires will naturally make the system weak mechanically. If joints can therefore be avoided altogether, one of the main weaknesses in an element will disappear.

(6) COOKING UTENSILS.

The construction should be such that any intelligent person can replace an element, simply by removing a nut, or otherwise. A saucepan which has given every satisfaction is shown in Fig. 10.* It is fitted with the type of element illustrated in Fig. 9. Replacement is very easy. The saucepan may also be dipped into a bucket of water without endangering the element, in spite of the fact that the lower portion is not soldered to the upper one. There are two spirals fixed to a sheet of mica, for 600 and 400 watts respectively, which may be used separately or in parallel and in series, so that 1 000 watts, 600, 400 and 250 watts may be obtained. A suitable loading of such a vessel is about 4 watts per cm² of surface, though it may be raised to 5 watts. Aluminium or tinned copper will be found satisfactory for such saucepans. Pure nickel is now coming into fashion and gives excellent results, but is expensive.

Pure nickel is undoubtedly the best material that can be employed, as it has a very high melting point and is easily kept clean. It has also a high scrap value.

Aluminium possesses the disadvantage of a low melting point, and results have usually been very unsatisfactory. With the element shown in Fig. 9, aluminium vessels may be used with complete satisfaction. Between the heating wire proper and the metal of the saucepan there lies only a thin sheet of natural mica, so that the heat is conducted away very rapidly, and the temperature-drop between the heating wire and the metal of the saucepan is small. There is thus no necessity for employing very high temperatures, and 600–700° C. for the heating wire will suffice. The author has used in his own house aluminium saucepans for over 3 years, and they are still being used daily.

* British Patent No. 215539.

It is also a curious fact that heat preserves aluminium, and a saucepan with an element will last much longer than one without an element, care of course being taken that there is always something in the vessel when the current is on; otherwise the element shown in Fig. 9 will melt the saucepan. Even this, however, will not destroy the element. The action of heat counterbalances that of chlorine contained in the water.

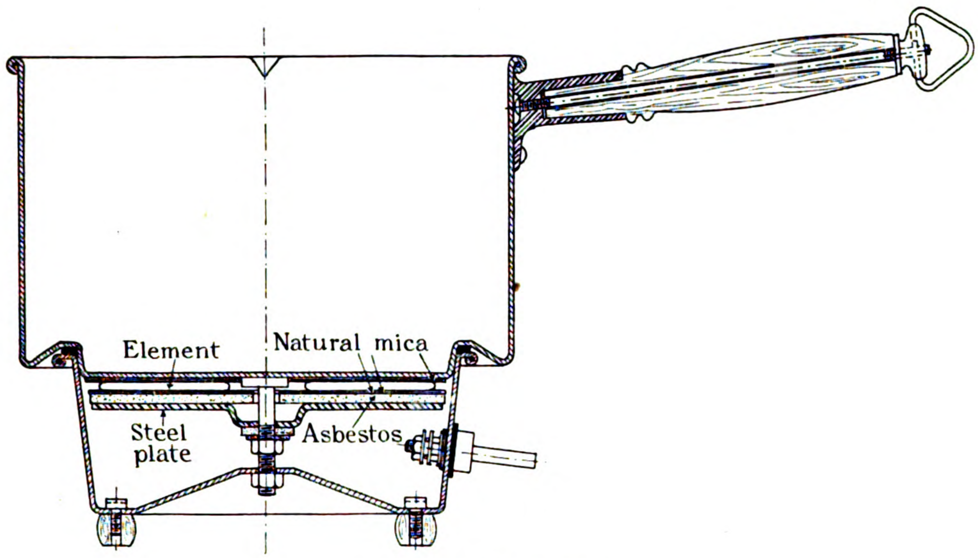

FIG. 10.—Saucepan.

Tinned copper possesses the disadvantage of requiring retinning fairly frequently. For large saucepans, tinned iron has also been used.

Large vessels should always be lagged to reduce the loss of heat.

The efficiency of the $2\frac{1}{2}$ litre saucepan shown in Fig. 10 was 88 per cent when bringing cold water to the boiling point for the first time. This shows the great advantage of the saucepan with an element, over the use of hot-plates.

In the tests given below for hot-plates the experiments were carried out with great care, all the vessels being a close fit. In an ordinary kitchen the efficiencies would be much lower.

(7) HOT-PLATES.

The author does not advocate the use of hot-plates. They are slow and inefficient, especially if ordinary ill-fitting cooking utensils are placed thereon. In an ordinary household the hot-plate is usually employed for one operation only, when the efficiency will rarely be more than 40 per cent, even if the greatest care is taken, and it may be as low as 30 per cent. Yet in spite of this fact, large electric ranges with numerous hot-plates are still being manufactured, with the result that those who buy them, mostly at a high price, soon find out that they cannot afford the bills for current at the end of the month. This has been proved over and over again in this country. Properly constructed cooking saucepans are preferable in every case.

There are two types of hot-plates on the market, the open spiral type and the enclosed plate type. The former has the advantage of cheapness but is often easily damaged by liquids boiling over.

The efficiency depends largely upon the weight of the plate and whether it is used for one operation only or for continuous work. The burning out of an enclosed hot-plate if left standing idle under current may be prevented by supplying the plate with corrugations. Such a plate is shown in Fig. 11. Even if made of aluminium it can be left idle under full load for $\frac{1}{2}$ hour or more, whilst if made of cast iron it can be used as a radiator.*

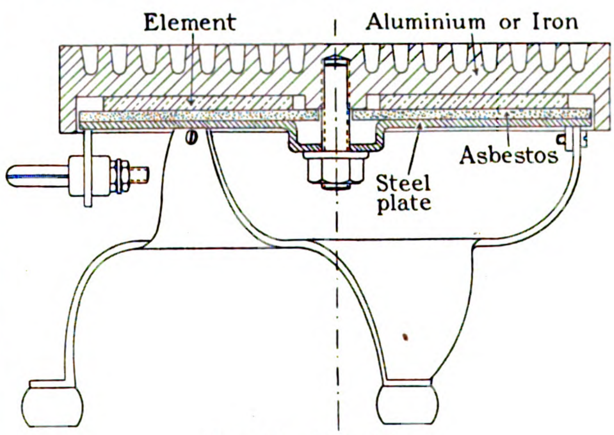

FIG. 11.—Hot-plate.

It may also be used as an element for a baking oven, for which it has proved very satisfactory.

Comparative tests were carried out with two different types of hot-plates, one of which was very light † whilst the other one was heavy. In both cases the same

* British Patent No. 219497.
† The light plate used would not be substantial enough for household purposes.

cooking utensil was employed and the same quantity of water was brought to the boiling point. The results of the tests are shown in Fig. 12, which is for 2 250 grammes of water in a vessel with a total content of about 6 litres. The tests show conclusively that a heavy hot-plate is a very inefficient article if the operation is to be performed once only and if the quantity of water or food is small.

When the quantity of water was increased to 4 000 grammes the efficiency of the lighter plate fell from 71 to 66·4 per cent, whilst that of plate B was increased from 31 to 44·3 per cent. When the plates were used a second time immediately after the first operation, the efficiency of the light plate increased by only 4 per cent (from 71 to 75) whilst that of plate B rose to 66·8 per cent. This shows that a heavy plate is suitable for continuous work and large quantities, a light plate for single operations, and that the light plate, which absorbs only 850 watts against the 1 766 watts of the heavy plate, is too small for large quantities. For every 1 000 grammes of water to be boiled the power taken should be at least 400 watts. In fact, it generally pays, at least from the standpoint of current consumption, to employ large powers and do the work quickly, rather than to use little power and much time.

After the cooking operation has been completed the energy stored in a heavy plate may be usefully employed for heating washing-up water. With the heavy plate 14 per cent was recovered in this way.

The experiments were repeated with an open grill type of hot-plate. For 2 250 grammes of water and a reflector below the heating wire the efficiency which resulted was 55·7 per cent when the bottom of the aluminium saucepan was highly polished. After painting this surface a dead black the efficiency rose to 66·9 per cent. The dead-black surface stops most reflection. When a highly polished "whistling" can was used the efficiency of the open grill without reflector was only 31 per cent; when the bottom was painted a dead black the efficiency rose to 62 per cent.

These simple tests indicate in what direction the efficiencies of hot-plates may be considerably raised.

A hot-plate in which the heating element consisted of rods of "silit" was also tested. The efficiency which resulted with 2 250 grammes of water was 54 per cent, the under-surface of the vessel being black.

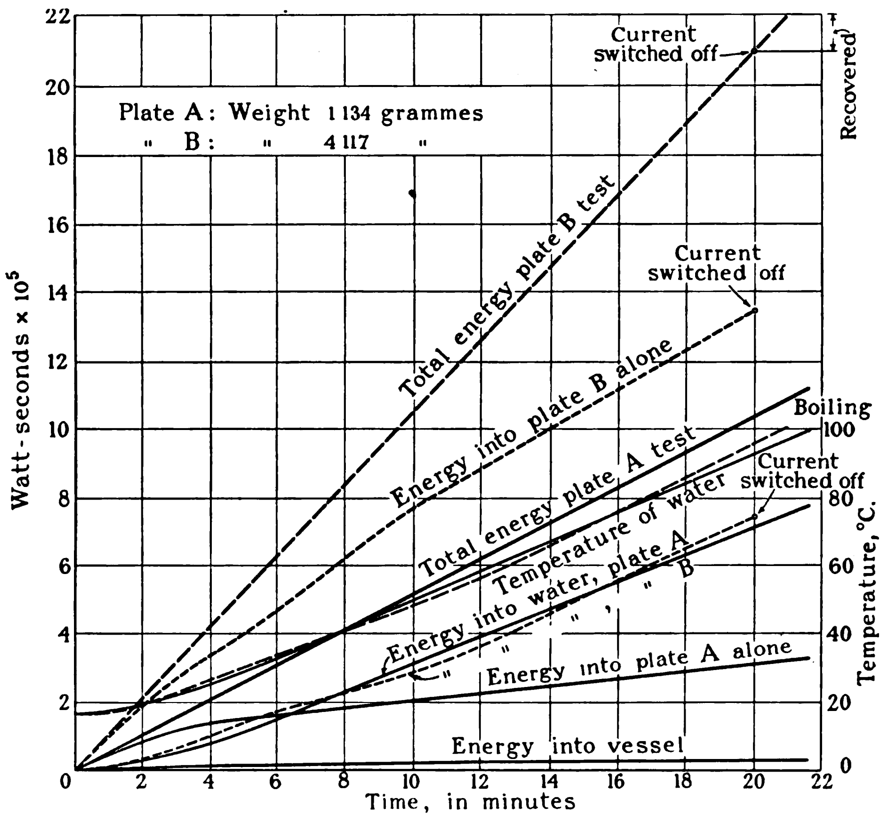

FIG. 12.—Tests on hot-plates.

A NEW SYSTEM OF CONTROL FOR ELECTRICALLY DRIVEN WINCHES AND CRANES.*

By J. Bentley, Associate Member.

(*Paper first received* 28*th August, and in final form* 10*th November,* 1925.)

Summary.

In the first part of the paper the author reviews the conditions which an electric winch or crane should fulfil, and discusses the different ways in which these can be met and the difficulties and disadvantages entailed.

An arrangement of contactors, resistances, etc., together with a patent speed-load device, is described as applied to an electric winch, and its method of working and performance under various conditions of hoisting and lowering loads are detailed.

A simpler, more compact and less costly system, obtained as the result of experiment, is developed, with curves giving the various speeds obtained at different loads and a description of the safety devices, etc., incorporated.

In providing an electric drive for a winch or crane to raise and lower loads, the following requirements must be arranged for :—

(1) To lift the load at suitable speeds.
(2) To hold the load from running back.
(3) To allow the load to be lowered under control.
(4) To prevent the load from being lowered at a speed beyond that at which the centrifugal forces set up in the armature reach a safe limit.
(5) To take up the slack in the cable without undue strains upon the gear when the slings tighten on the load.
(6) To drop the load carefully and without damage.
(7) To drop the load smartly when on the swing, and to make it respond to the operator's will as promptly as possible.
(8) To prevent the motor and gear from being overloaded.
(9) To prevent the motor from running back or re-starting if the power should fail without the operator's knowledge.
(10) To obtain good acceleration and retardation, thus enabling the cycle of operations to be completed as speedily as possible.

These requirements will now be considered in order.

(1) *To lift the load at suitable speeds.*—A series-wound motor with a suitable starting resistance, connected to a winding barrel through suitable gearing, is the prevailing practice, the diagram of connections being given at A (Fig. 2).

The relation between loads and lifting speeds is shown in Fig. 1 (curve A). This curve shows speeds varying as $1/\sqrt{T}$, where T is the torque, lower speeds being obtained by regulating the resistance. The speeds given by this arrangement compare unfavourably with those obtained from a steam or hydraulic winch or crane, since where the loads to be handled vary in weight the speeds at the light loads are too low. This curve can be improved by using a motor with an arrangement for field adjustment. The ideal amount of field regulation is that which causes the motor to take full current at any load and gives speeds as shown by

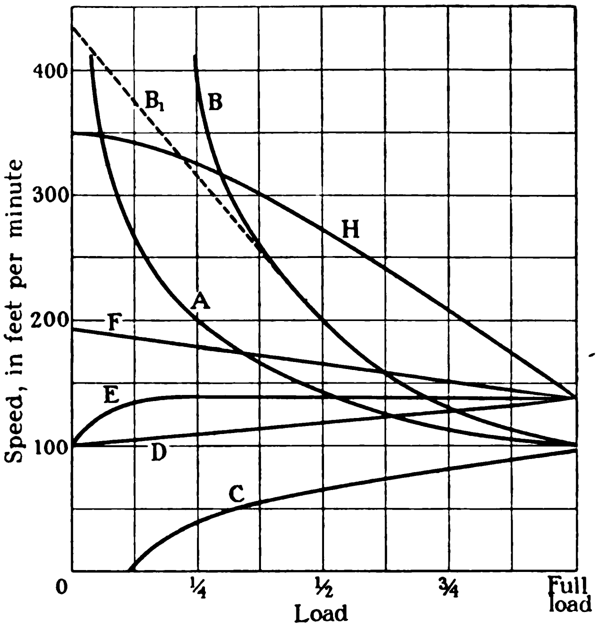

Fig. 1.

curve B in Fig. 1. Here the speed varies as $1/T$, T being the torque. This is only desirable for those loads above, say, ¼ full load, and it is not practicable so to arrange the design of the motor. This result can, however, be attained to all practical purposes by designing a motor to give twice full-load speed at one-half full load.

With a series motor the best way to arrange for field adjustment is by diverting current from the series winding, the amount diverted being arranged according to the load. This changes curve B (Fig. 1) to the dotted curve B_1. The connections are given in diagram B (Fig. 2).

Provision has to be made for the starting resistance

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

to be cut out in proper increments, and time must be given for each surge of current to return to normal before the next step of resistance is cut out. This is done either by training the operator to start up gradually or by fitting some timing arrangement to prevent him from starting up too quickly. It is standard practice to divert the series winding after all the starting resistance is cut out. This keeps the current-kicks down when starting up. In practice it is found to be unnecessary to time the rate of diversion as the inductive effect of the field winding does this automatically.

The question of field diversion also arises in connection with acceleration. It is difficult for the operator to judge how much diversion to use in order to attain the requisite speed for a load of which he does not divert the series field to give a predetermined speed for a given deflection, i.e. a given torque.

The contacts R are connected to the coil of a circuit breaker and are arranged to open the latter when the load exceeds a prearranged value.

(2) *To hold the load from running back.*—The usual method of doing this is to fit a magnetic brake, i.e. a brake which comes into operation when the supply is disconnected from the motor.

Another arrangement is to hold the load by short-circuiting the motor across its own series winding, connection being made so that the motor acts as a generator. To obtain this braking effect, the series winding must be connected so that the current passes through it in the opposite direction to that in which it does when hoisting.

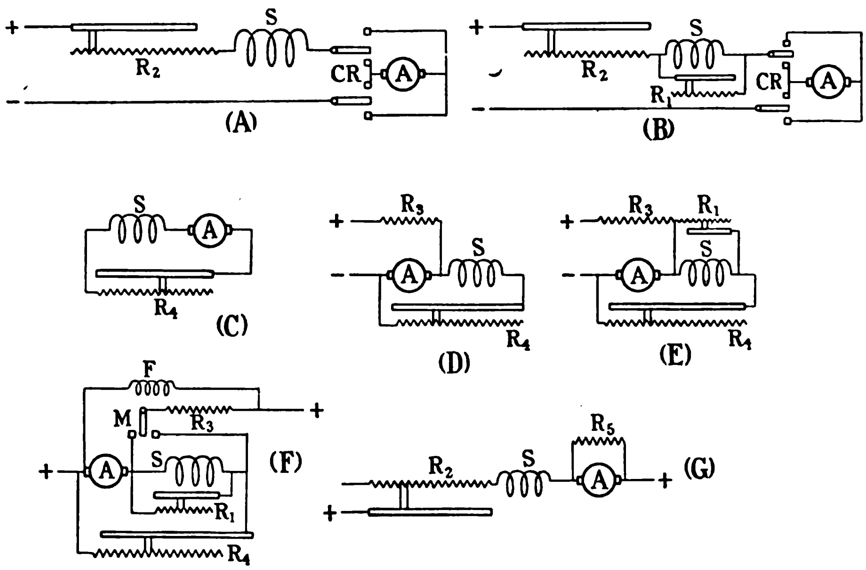

FIG. 2.

A = armature
S = series winding
R_1 = series diverter rheostat
R_2 = starting resistance
R_3 = lowering starting resistance
R_4 = variable resistance
F = shunt winding
CR = reversing switch
R_5 = armature diverting resistance

know the weight. The steps can be marked for various weights, but, unless the weight of a particular load is known, the operator cannot take advantage of this.

To be really advantageous the field diversion must be done automatically. One method of bringing this about is given in Patent No. 218461, the description of which is as follows :—

The motor is connected to the winding barrel through gearing of the sun and planet type (see Fig. 3). The centre sun wheel 22 is connected to the armature, and the three planet gears, 20, to the load. The internal gear 19 is arranged to float and is anchored through the spring 18. This spring balances the reaction tending to revolve the gear 19, the deflection being in direct proportion to the torque being transmitted.

The motion of the gear 19 is transmitted to a sliding rheostat 13, the stepping of which is graded so as to

If the motor is hoisting the load and the controller is brought to the "off" position, it is only necessary to short-circuit the armature across the series winding to obtain the braking effect, since when the armature reverses its rotation the current changes in direction, the armature passing current through the series winding in the same direction as for hoisting.

The objection to this method is that the motor must be in motion to obtain the required effect.

The load creeps slowly under these conditions, and if it is required to be held a foot brake must be fitted.

The advantages of this method of braking are dealt with under heading (7).

(3) *To allow the load to be lowered under control.*—There are several mechanical devices in use to prevent the load from taking charge, but the majority of them do not permit its control at a definite speed. A foot brake will do this, but due to the constant readjust-

ment required this method is found in practice to be unreliable. The load can be controlled quite simply electrically by using what is known as rheostatic braking, that is, arranging the motor to act as a dynamo, supplying power to a variable resistance.

Diagram C (Fig. 2) gives the connections and the speeds are as shown by curve C (Fig. 1). This arrangement is very simple and reliable so long as the load will overhaul the motor and is sufficiently heavy to overcome the mechanical and electrical losses.

When lowering lighter loads it is necessary to use power. The operator must be trained not to switch over to the power steps for heavy loads, and to come back on to the braking steps gradually, otherwise the voltage generated will be sufficiently large to cause the motor to flash over. This system is often used, but it is usual to fit a mechanical device to prevent excessive speeds should the operator apply power when lowering a heavy load, and also to install a timing arrangement to prevent the braking steps from being put into operation too quickly.

In order to overcome these difficulties a system of electrical braking known as potentiometer lowering can be used. The connections used are shown in diagram D (Fig. 2). This system consists of rheostatic braking, with the addition of current from the line. While the load is overhauling the motor the latter acts as a brake, but should the load be too light to do this the power supplied from the line rotates the motor, the series winding acting as a very inefficient shunt field.

Unfortunately, the system is very inefficient and the lowering speeds are limited, the speed with the hook light being approximately the same as the full-load hoisting speed (see curve D, Fig. 1). These lowering speeds can be improved for the lighter loads by having a series diverter as for the hoisting side, using the device described in connection with requirement (1) (see diagram E, Fig. 2). This diverter is variable according to the load being lowered. It was found, when fitting it, that the diverter must be disconnected before short-circuiting the resistance R_4 in series with the motor. The load falls and then pulls up with a jerk when the current-surges die down, and the motor has a tendency to flash over, this being caused by the machine ceasing to generate due to the self-induction of the field, the current passing through the diverter instead of through the field winding.

It will be seen from curve E, Fig. 1, that this arrangement only improves the speeds of loads which will drive the motor, the light-load speeds being still very low. These can be improved by adding a shunt winding to the motor and automatically changing over the current from the line to the other end of the series winding after the motor has got up to speed (see diagram F, Fig. 2). This addition weakens the field, since the series winding opposes the shunt, and gives the speed curve F, Fig. 1, but if the load is one which drives the motor the series winding helps the shunt winding and the load is still controlled.

The change-over of the connection from one end of the series to the other must be made automatically when the voltage on the armature has reached a certain value and the starting current has fallen to that required for light running, or when the load is sufficient to drive the motor; and the contactor must change back again if the current is too high, otherwise the motor will reverse and race due to the series winding overpowering the shunt. Under these conditions the motor is running with a weak field, and to supply the required torque the armature takes more current. As the field gets weaker the current taken by the armature rises, torque being proportional to the armature current and field flux, therefore the effect is cumulative.

Higher light-load speeds, as shown by curve H (Fig. 1), can be obtained with this arrangement of connections if provision is made for the insertion of a comparatively high resistance. The load is now controlled by the motor generating to the line. One precaution that must be taken is that the braking resistance must be automatically reduced if the power fails, otherwise the load will be out of control. An excess-voltage relay must operate to prevent the no-voltage device from being energized by the motor acting as a generator. The most critical period for this tendency to energize the no-volt circuit is when lowering medium loads, the heavier loads taking some time to attain generating speeds and allowing the no-voltage release to act first.

In dealing with this it was arranged to break this circuit altogether instead of inserting a high resistance in series with the braking resistance, but it was found that the rush of current from the line through the series winding in opposition to the shunt demagnetized the field and prevented the generating condition from coming into action. It is very probable that if the load had been allowed to drop far enough the motor would have started to generate, but it was not possible to test this because the speed attained would have been unsafe.

(4) *To prevent the load from being lowered at a speed beyond that at which the centrifugal forces set up in the armature reach a safe limit.*—To prevent the motor from attaining an excessive speed when lifting "light hook" a shunt winding to limit the speed to any required amount can be fitted. This shunt will not, however, limit the speed when lowering heavy loads, the reason being that the motor will tend to generate back on to the line, exciting the series winding in the opposite direction to the shunt.

A very common method of preventing excessive speed under any condition is to fit a centrifugal brake, i.e. a governor which applies a mechanical load when the speed reaches a definite value.

When using ordinary rheostatic control there is always one critical load which will cause the motor to race, even if the gearing is inefficient. This occurs when the load just balances the losses in the gearing and the motor, and the only reason that this trouble is not met with in practice is that the torque required to overcome the losses increases as the speed rises, while the torque exerted by the load remains constant.

Rheostatic braking and potentiometer lowering overcome the trouble of excessive speed when they are used in conjunction with a series motor, always provided that a power step without the braking resistance is not used. This means that the motor must be always

connected so as to be capable of generating across the resistance should the load be heavy enough to drive it. If, however, the gearing is very efficient a limiting shunt winding or centrifugal brake must be fitted for hoisting "light hook."

Mechanical devices which apply a brake when the load is driving the motor are sometimes used, but

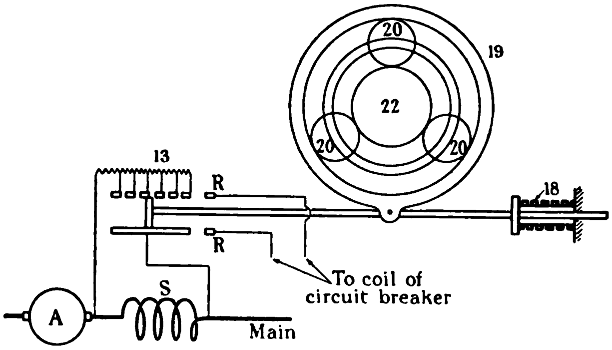

FIG. 3.

these do not prevent the latter from racing when the load just balances the mechanical and electrical losses, or when hoisting "light hook."

(5) *To take up the slack in the cable without undue strains upon the gear when the slings tighten on the load.*—To take up the slack in the rope steadily is only possible with ordinary rheostatic control by "teasing" the controller off and on, and is very difficult to perform satisfactorily.

The resistance in series with the motor does not absorb the voltage necessary to bring about the required reduction in speed until the machine is loaded.

To obtain a creeping speed a foot brake can be fitted to load the motor and reduce the voltage upon it, but it must be so interlocked with the controller that it cannot be used on any step of the latter which will pass sufficient current to overload the motor. It is best to arrange to use the foot brake on that controller step on which it can stall the motor with the power on, without passing an excessive current.

Another method of reducing the voltage on the motor armature is to insert a resistance across it, as in diagram G, Fig. 2. This arrangement passes current through the resistance and the series winding, increasing the field and reducing the voltage to the required value.

(6) *To drop the load carefully and without damage.*—The load can be lowered by hand-releasing the magnetic brake, if fitted, or by means of a foot brake, but this is liable to cause the load to drop in jerks.

Where potentiometer lowering or rheostatic braking is fitted, loads can be lowered at very low speeds which give very steady and easy landing.

The amount of resistance inserted in the generating circuit limits the speed to the desired value.

(7) *To drop the load smartly when on the swing, and to make it respond to the operator's will as promptly as possible.*—The operator should be given every facility for dropping the load smartly to enable him to clear obstructions. One disadvantage of fitting a magnetic brake is that the time taken by the brake to release prevents the load answering the controller quickly.

Where potentiometer lowering or rheostatic braking is fitted, the load is always alive and, provided it is heavy enough to overhaul the gearing, or the current from the line is sufficient to supply ample torque to the motor, the load will answer instantly.

For comparison between the accelerations given by the two methods, see the speed/time curves given in Fig. 4. The delay caused by the magnetic brake is at once apparent.

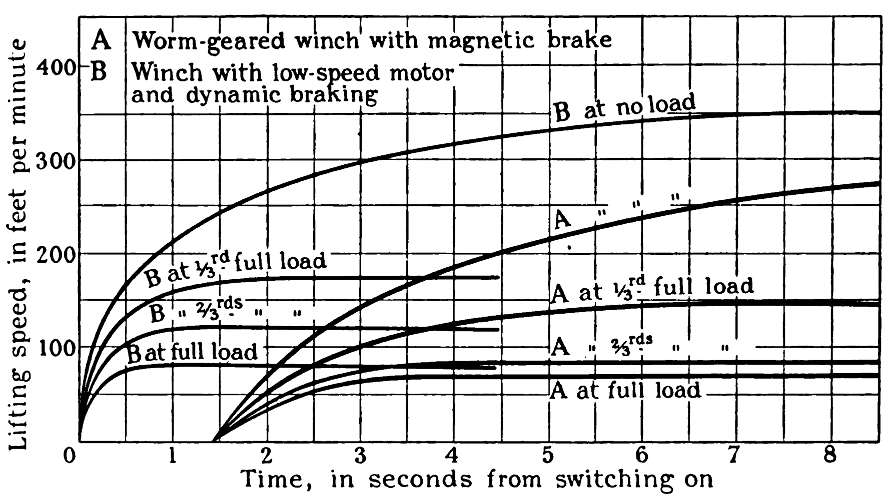

FIG. 4.

(8) *To prevent the motor and gear from being overloaded.*—The motor can easily be protected from overload by fitting fuses or an overload circuit breaker, but it is very difficult to provide against excessive stresses in the gearing and rope. Should an overload occur, the fuses or circuit breaker will act, but, whilst this protects the electrical equipment, the gearing and rope are strained due to the flywheel action of the

motor armature. This trouble can be avoided to some extent by measuring the load on the gearing side as described under heading (1), and arranging for this device to open the circuit breaker. By this means the duration of the overload is made as short as possible.

The time-lag of the current rising in the motor being obviated, the fitting of time-delay fuses or a time-element overload circuit breaker only aggravates the matter by lengthening the period of overload.

The circuit breaker, which is operated by the measuring device, should be self-replacing when the overload is removed, so that the operator can be independent of outside help.

Fuses and circuit breakers should be used only for a lifting motion as a protection against earths or defective electrical circuits, a sufficient time-delay action being arranged so that they may function after the mechanically operated circuit breaker. These should only be replaced by members of the skilled staff.

Strains on the mechanical gear and rope should be reduced by keeping down the angular momentum of the moving parts as much as possible.

addition, the motor must be prevented from running back if the power fails. This is dealt with under requirement (2).

(10) *To obtain good acceleration and retardation.*—The best results as regards acceleration and retardation are obtained by fitting an armature of low speed and as low a moment of inertia as possible and by the use of efficient gearing, the problem being not so much to accelerate the load as to accelerate the armature and other rotating parts. For instance, in the case of a winch fitted with a high-speed armature to lift 4 tons at 80 ft. per min. with a gear ratio of 26·5 to 1, the additional torque required at the armature to accelerate the load up to full lifting speed from rest in 1 second is about 120 lb.-in.

To accelerate the rotating parts up to this lifting speed from rest in the same time, the torque required at the armature is about 9 300 lb.-in.

With a low-speed armature of correspondingly larger size and with a small gear ratio, the rotating parts can be accelerated more quickly, as will be seen from the figures in Table 1.

TABLE 1.

Type of motor	Gear ratio	Moment of inertia of armature	Torque to accelerate armature	Torque to accelerate load	Normal torque to lift full load
			lb.-in.	lb.-in.	lb.-in.
High-speed (500 r.p.m.)	26·5 : 1	180 inch-lb. units	9 300	120	2 700
Low-speed (75 r.p.m.) ..	4 : 1	3 800 inch-lb. units	30 000	750	18 000

If the overload device has operated due to dead weight, the stresses in the rope and gearing are limited to this excessive load.

With the ordinary type of motor fitted to a crane or winch, the tension in the lifting rope to pull up the armature to rest from its normal lifting speed is about 80 times the required pull in the rope to bring the load to rest from the corresponding hoisting speed in the same time.

If the hook catches in some obstacle the stress in the rope is very great, due to the revolving parts, and can only be limited by making the angular momentum of these parts as low as possible and by fitting a powerful brake to pull up the revolving armature and gearing.

If the momentum is high the braking power must act quickly, and this in itself puts excessive stresses on the mechanical parts. A slipping clutch can be fitted to slip at a given load, to prevent excessive strains.

(9) *To prevent the motor from running back or re-starting if the power should fail without the operator's knowledge.*—If the power fails it should not be possible for the motor to start up again when the power is restored, if the controller has been left in the running position. The usual method of ensuring this is to make it necessary for the operator to come back to the "off" position before re-starting, by fitting a mechanical or electrically operated circuit breaker. In

In each case the winch is rated to lift 4 tons at 80 ft. per min.

The last column gives the normal full-load output expected from the motor, and it is apparent that the quick acceleration of the armature causes a heavy overload on the motor. In the case of the high-speed motor this overload is 3½ times full load, but with the low-speed armature the overload is only 1·7 times normal full load. Thus better acceleration can be obtained by fitting a motor of the low-speed type.

To run a motor up to speed quickly the difference between the applied voltage and the back E.M.F. must be kept as great as possible consistent with the overload which the motor will stand.

It is very difficult to obtain good acceleration at light loads, the reason being that the back E.M.F. rises quickly, whilst the field is slow in dying down.

Best acceleration is obtained under these conditions by weakening the series field by diversion at the start, an automatic diverter setting the field strength at the normal value for any particular load. The field strength is kept low and the armature current high.

It was found that by fitting a very low-speed armature that the motor could be started up without the use of timing arrangements on the contactors, the self-induction of the field windings being sufficient to limit the current to prevent sparking.

With the foregoing in view, the author considers that the best way of meeting these requirements and coping with the difficulties mentioned, is as follows :—

(1) To obtain the required lifting speeds the motor should have a field range of at least 2 to 1 by automatic field diversion, giving a speed curve as shown at B_1, Fig. 1.

The rushes of current should be kept down by having a highly inductive series field winding.

(2) The motor to be short-circuited across itself so as to generate should the load tend to lower.

(3) In order to keep the load under control, a form of rheostatic braking, with power from the line to lower light loads, should be fitted. A series diverter and shunt winding should also be fitted so as to get high light-load lowering speeds, the speeds suggested being as shown in curve H, Fig. 1.

(4) To prevent excessive speeds the rheostatic braking, and those arrangements for returning power to the line, must always be in operation even if the operator switches over to the light-load steps when lowering a heavy load.

(5) To obtain low-speed control on the hoisting motion an armature diverter should be fitted to reduce the effective voltage on the armature, or a foot brake should be applied to absorb the voltage in the main resistance.

This foot brake should be so interlocked that it cannot be operated without returning the controller to a step that will not overload the motor.

(6) "Dead slow" lowering speeds to be obtained by fitting rheostatic braking.

(7) In order that the load may answer quickly, rheostatic braking with sufficient power from the line to give good acceleration should be provided.

(8) Overloads to be prevented by measuring the load on the gearing side of the motor and arranging this device to open a circuit breaker when an overload occurs.

In addition, the angular momentum of the revolving parts should be limited, as far as possible, so that they can be arrested without the rope and gearing being unreasonably stressed.

Fuses or circuit breakers to be fitted only for electrical faults and to be supplied with timing arrangements to prevent them from operating before the mechanically operated circuit breaker, the former to be replaced only by the skilled staff.

(9) To provide protection against the effects of restoration of the power after failure, a no-volt circuit breaker to be fitted which can only be replaced when the master controller is in the "off" position.

(10) The rates of acceleration and retardation to be made as high as possible by fitting a low-speed armature with small moment of inertia, giving low angular momentum.

The starting gear should be so arranged that the current-kicks applied to the motor are as high as possible until the motor is up to speed, the machine being designed to stand these heavy rushes of current.

The series winding should be diverted before the starting resistance is cut out in order that the field strength can be kept down, thus avoiding the slow change of field due to self-induction.

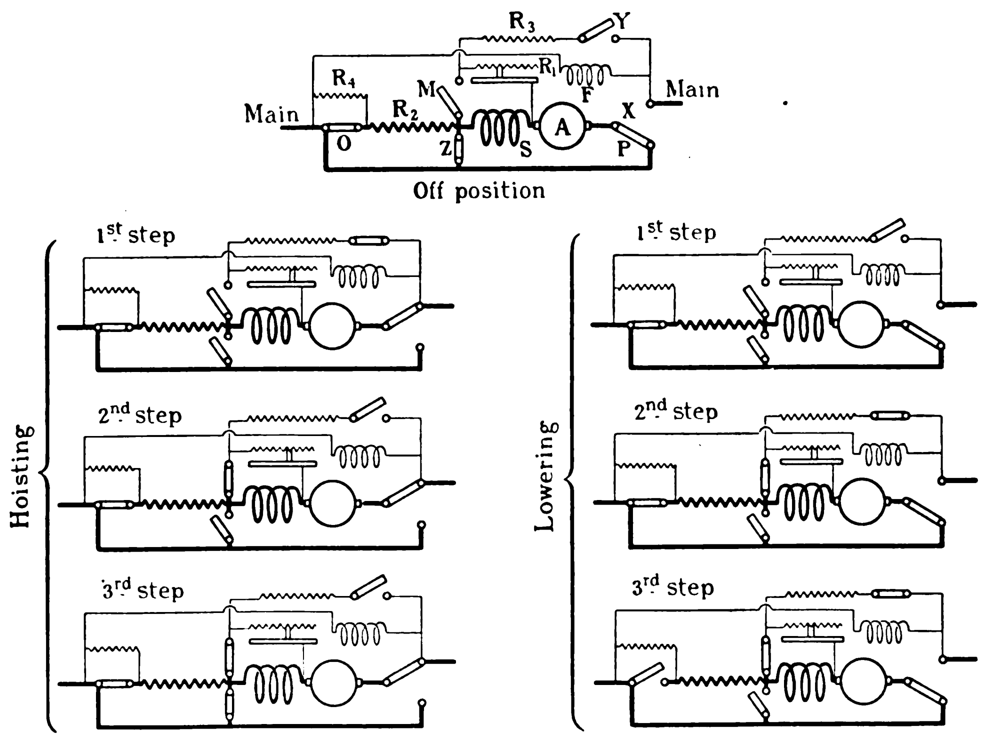

FIG. 5.

The connections which collectively provide for these conditions are shown in Fig. 5. The armature is denoted by A; S denotes a series field winding of value 90 per cent of the required field ampere-turns; F denotes a separately-excited shunt field winding of value 25 per cent of the total ampere-turns for lowering and 10 per cent for hoisting; R_1 is an automatically operated series diverter rheostat as in Fig. 3; R_2 is a starting and regulating resistance of such ohmic value as to give half speed with full-load current; R_3 is a starting resistance for lowering light loads; and R_4 is a resistance to be inserted to obtain high light-load lowering speeds. This resistance was found necessary as an alternative to breaking the circuit to ensure the excitation of the motor when lowering heavy loads. It is of such ohmic value as to pass 15 per cent of the full-load current with the series field, armature, and R_2 in series across the mains.

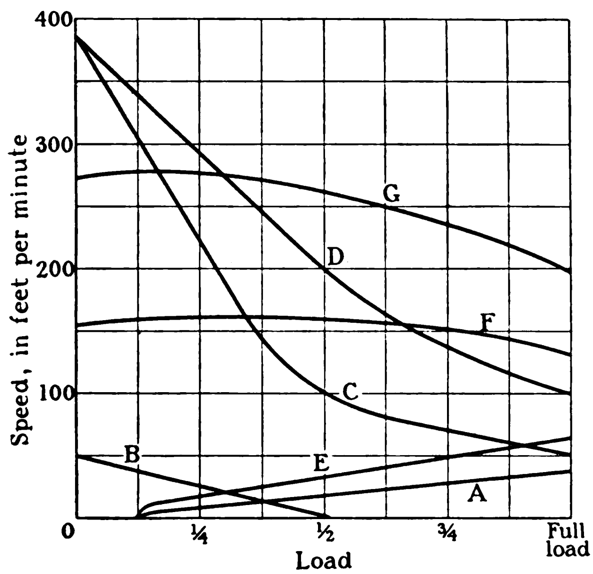

FIG. 6.

XP denotes a change-over contactor operated by a coil which, when energized, closes the side X, the contactor normally remaining in position P when the controller is placed in the off position or when the voltage fails.

O and Y are contactors which close when their operating coils are energized from the line voltage.

M denotes a contactor which closes when its operating coil is energized by the armature voltage.

Z denotes a contactor which opens when its operating coil is energized by the line voltage, and closes when the power fails.

It is preferable that these contactors be electrically operated, as the change-over connections are then more easily arranged. With mechanically operated contactors difficulties arise in the no-volt condition.

With the master controller in the " off " position the change-over contactor XP is closed in position P and contactors Z and O are also closed, the motor armature being connected across its own series winding. If the load is sufficient to drive the machine, the latter acts as a dynamo, the speed of lowering being dependent on its internal resistance.

Suppose the voltage-drop in the armature and series winding with full-load current to be X volts, and the line voltage to be Y volts, then the ratio of normal speed to lowering speed is given by $(Y - X)/X$.

For loads below full load the speeds must be adjusted for alteration in field strength due to the shape of the magnetization curve. If the field strength were directly proportional to the ampere-turns the speed would be the same for all loads (see curve A, Fig. 6).

Three hoisting and three lowering steps, in addition to the " off " position, are provided on the controller, and these act as follows :—

1st hoisting step.—The change-over contactor XP moves from position P to position X. Contactor Z opens and contactor Y closes. This connects the armature and series winding in series with the starting resistance across the mains and with a resistance in parallel with the armature. The speeds obtained are shown by curve B, Fig. 6.

2nd hoisting step.—Contactor Y opens and disconnects the resistance in parallel with the armature.

Contactor M closes and connects the automatically operated diverter rheostat across the series winding.

The amount of current diverted depends upon the load. If the motor is fully loaded, the diverter is cut out. Half full speed is obtained for any load above half full load with a certain value of starting resistance. The speed can be varied by varying the value of this resistance. For lower loads the speeds are proportionally lower. Curve C, Fig. 6, gives the speeds obtained.

3rd hoisting step.—Contactor Z closes and short-circuits the starting resistance. The motor is now connected across the mains with its series winding diverted for any load below full load (see curve D, Fig. 6).

1st lowering step.—The change-over contactor XP remains in position P as for the " off " position. Z opens and the armature and series winding are now connected across the starting resistance R_2. The load must be sufficient to drive the motor on this step (see curve E, Fig. 6).

2nd lowering step.—Contactor Y closes, connecting the motor to the line as a shunt motor with the series winding acting as an inefficient shunt winding.

When the voltage across the armature rises, contactor M closes, connecting the diverter across the series winding and connecting the main so as to supply current to the other end of the series winding.

If the load is not driving the armature, part of the current passes through the series winding so as to oppose the effect of the shunt winding, giving a weak field to keep up the speed for light loads.

If the load is already driving the motor the series winding helps the shunt winding and so keeps the load under control by generating across the resistance R_2 (see curve F, Fig. 6.)

3rd lowering step.—Contactor O opens, inserting the resistance R_4 in the dynamic braking circuit.

If the load is driving, the motor increases in speed

until the voltage is such as to cause it to generate back to the line.

While the motor is accelerating in order to attain a voltage to overcome that of the line, a small current is passing through R_4 to help the excitation (see curve G, Fig. 6).

When lowering light loads the value of the diverter must be such that the current in the series winding does not increase sufficiently to overpower the shunt. As the speed rises due to the weakened field, the current required to drive the armature increases and if the diverter does not take enough current the motor will reverse. Since the operating coil of contactor M is connected across the armature, if the motor tends to stop and reverse, this contactor will keep dropping in and out and the motor will hunt.

It should be noted that if the resistance of R_3 is of such a value as to allow rushes of current through the series winding heavy enough to overpower the shunt winding, the same conditions hold good (see curve G, Fig. 6).

It was found when using a winch fitted as described above that the master controller could be put over to any step without pausing on intermediate steps. For example, the operator could pass from full hoist to full lowering steps without the current exceeding about twice full-load value or causing any sparking on the commutator. Thus the control may be said to be perfectly foolproof.

When the connections in Fig. 4 are used for a deck winch on board ship a difficulty arises in that the winch may be required to lift or warp for either direction of rotation of the winch end. This difficulty can be overcome by fitting a reverser for the armature connections which remains locked unless the master controller is in the " off " position.

After experimenting with this arrangement of connections the author came to the conclusion that it could be simplified and the cost reduced on the following lines :—

(i) It is of very little use to have a motor with a series-wound characteristic, since the automatically operated diverter can be arranged to regulate a resistance to adjust the value of a shunt winding to give the required speed/load curve.

(ii) The motor would start up without resistances if the series winding could be arranged to give an inductive effect equivalent to that of the winding of a motor with a series characteristic, only a few ampere-turns being used for normal running, the rest of the current being diverted after starting.

(iii) The resistances being only necessary for speed regulation, these could be dispensed with if the shunt regulating resistance were short-circuited to give full field on the regulating step.

(iv) All the braking required for lowering can be done by regenerating back on to the line, provided an excess voltage relay is fitted to short-circuit the motor across its own series winding should the power fail.

(v) The required speeds with light loads, including no load, can be attained by arranging an electrically operated reverser which discriminates automatically as to whether the machine is motoring or braking.

To obtain the desired conditions a motor of low-speed type is used, with a field winding of high enough resistance and sufficiently inductive to keep the starting current within the sparking limits of the motor without the use of starting resistances being necessary.

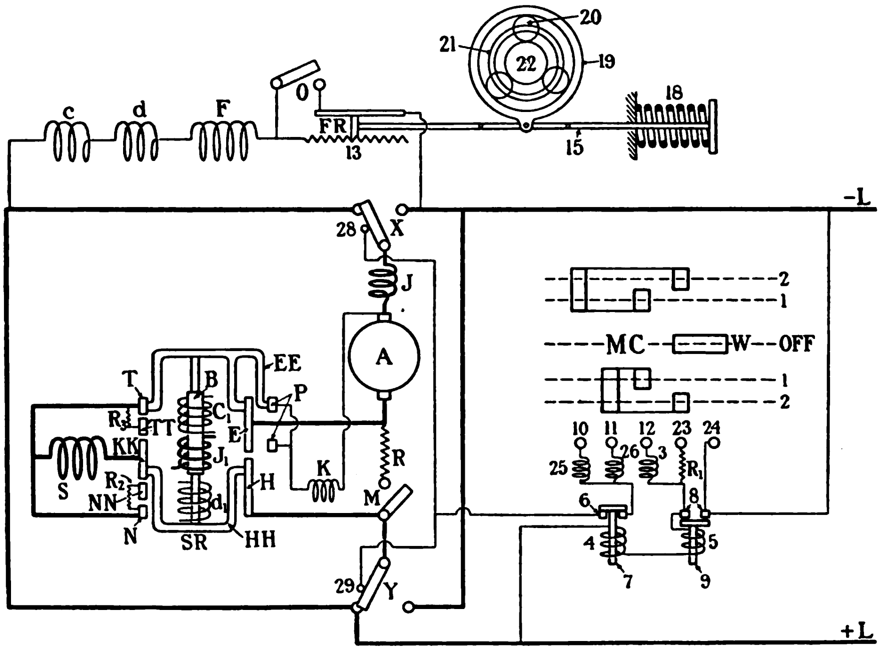

FIG. 7.

In Fig. 7 the armature is denoted by A. S denotes the series winding which has sufficient turns to give the required field, when carrying a current within the limits of the motor, to supply sufficient torque to resist the full load when the machine acts as a series generator. This series winding has to carry full current only for a short time when starting up, so need only be of small current-carrying capacity.

F is a shunt winding with sufficient ampere-turns to supply the principal part of the field flux.

FR is a variable rheostat operated mechanically as previously described, but in this instance the rheostat movable contact 13 inserts a resistance in series with the shunt winding F, the maximum resistance being inserted when hoisting or lowering "light hook" and the whole of the resistance being cut out for full load.

O is an electrically operated contactor which, when its operating coil 3 is energized, makes circuit and cuts out the resistance in the variable rheostat "FR."

X and Y are electrically operated change-over contactors which connect to the main (+ L) when their operating coils 25 and 26 are not energized, either being able to connect to the main (— L) when its operating coil is energized.

M denotes an electrically operated contactor which makes circuit when its operating coil K is energized by the voltage across the armature A.

R denotes a diverter resistance which shunts sufficient current out of the series winding S, when contactor M closes, to keep the current within the carrying capacity of the winding.

SR is an electrically operated reverser which acts in the following manner :—

The fixed contacts E and H are connected, one to the armature A and the other through the contactor Y to the main (+ L or — L).

The fixed contacts T and N are both connected to one end of the series winding S, and contact KK to the other.

Coils c and d are connected in series with the shunt winding F and are arranged to oppose each other. Coil J is connected in series with the armature A. These coils are indicated in position on the reverser SR, coil c as C_1, coil d as d_1 and coil J as J_1.

B is an iron core which is mechanically connected to, but insulated from, movable contacts EE and HH.

R_3 and R_2 are resistances connected to the fixed contacts T and TT, and N and NN, respectively.

When the coils C_1 and d_1 only are excited, the iron core B takes up a central position ; the movable contacts EE and HH, being attached thereto, connect contacts E to TT and H to NN.

The current will then pass from the armature (A) through the resistances R_3 and R_2 back to the main (+ L or — L) through contactor Y.

If coil J_1 is excited to help coil C_1 and oppose coil d_1, the iron core B will take up a position between coils C_1 and J_1. The movable contacts EE will then connect contacts E and T, and the contacts HH will connect contacts H and KK, passing the current in the series winding in a prearranged direction so as to help the shunt winding F.

If coil J_1 is excited to help coil d_1 and oppose coil C_1, the iron core B will take up a position between coils d_1 and J_1, and the movable contacts EE will then connect E and KK and contacts HH will connect H and N, passing the current through the series winding S in the opposite direction.

A relay 4 breaks contacts 6 when the line voltage is exceeded by a predetermined amount. The relay 5 breaks contacts 8 when the line voltage fails.

The operating coils of 4 and 5 are connected across the mains (+ L and — L) through contacts 8 or 23 and 24.

The operating coils 25, 26 and 3 are connected across the mains through contacts 28 and 29 when the master controller drum MC is in one of the running positions, each of the coils being energized in turn according to the position of the master-controller contacts.

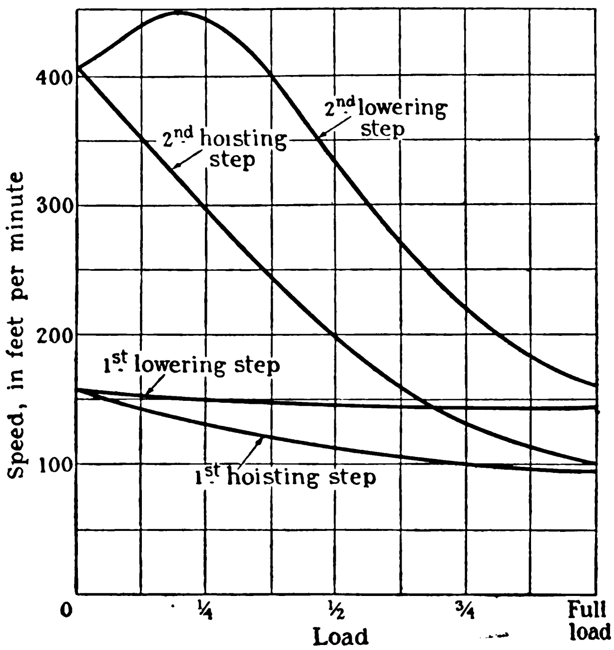

FIG. 8.

R_1 is a resistance having an ohmic value equal to that of coil 3.

MC denotes a master-controller drum fitted with connector pieces so that the connections through the finger contacts 10, 11, 12, 23, 24 can be altered in a prearranged manner at will.

The motor is controlled in the following manner : The master-controller drum MC, when in the "off" position W, connects contacts 23 and 24. This makes the connection through the relay-operating coils 4 and 5, lifting the relay plunger 9 and connecting contacts 8, enabling relay 5 to maintain its own operating circuit. Relay 4 is energized, but its contacts 6 remain connected unless the voltage on the motor exceeds the normal line voltage by a prearranged amount.

The operating coils 25 and 26 are not energized and the reversing contactors X and Y remain connecting both ends of the motor leads to the same main (+ L), leaving the armature (A) connected across the series

winding S, acting as a generator should the load tend to revolve the armature.

The shunt F and coils C and d are separately excited across the mains (+ L and — L) and decide the direction of rotation of the armature (A).

If the master-controller drum MC is moved to step 1, contacts 11 and 12 are connected and coils 26 and 3 are energized, changing over contactor X to connect to winding S always excites the magnetic circuit of the motor to help the shunt winding.

If the load requires to be driven the motor takes current from the mains, but if the load is driving the motor the back E.M.F. rises above the supply voltage and current is returned. If the master controller is moved to step 2, contacts 11 and 23 are connected, the current passing from main (+ L) through coil 26

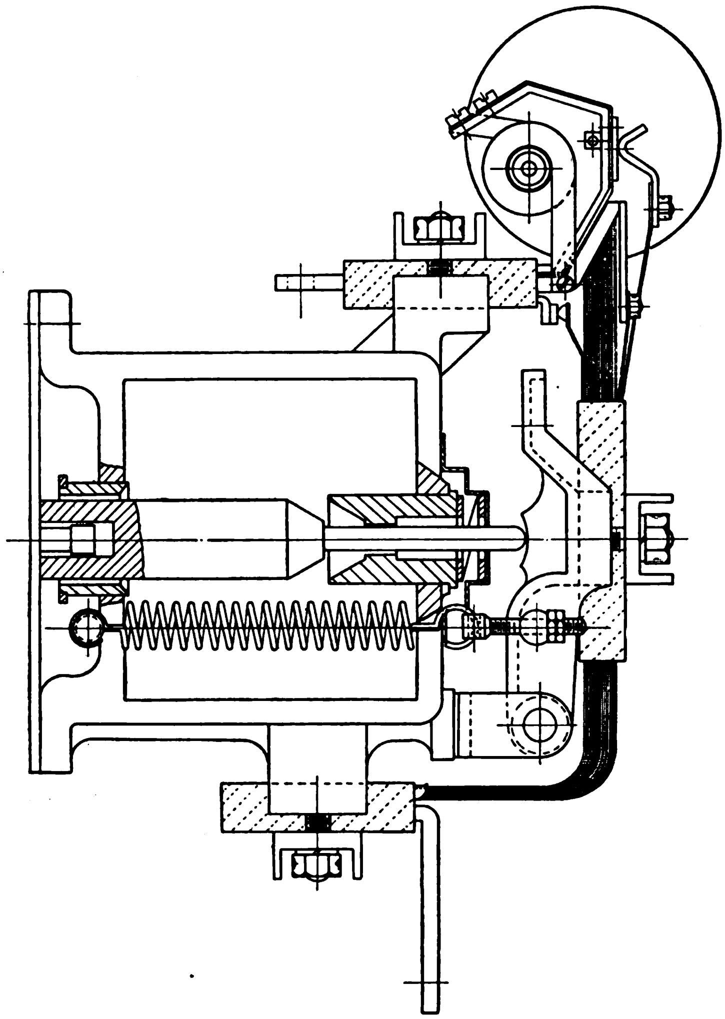

Fig. 9.

the main (— L). The motor is now connected across the mains and the variable rheostat FR is short-circuited by contactor O. The armature starts to rotate and, when the voltage across it reaches a predetermined value, the operating coil K being energized, contactor M makes circuit to diverter resistance R, dividing the current between this diverter and the series winding S.

From the description of the reverser SR it will be seen that the current passing through coil J in the same direction as through the armature decides which way current passes through the series winding.

The connections are so arranged that the series to the other main (— L), passing through resistance R_1 instead of coil 3.

Coil 3 not being energized, contactor O open-circuits any resistance that may be inserted by the variable rheostat FR. This weakens the shunt winding F for any load less than full load and an increased speed is obtained.

If the master-controller drum MC is moved in the opposite direction contact 10 is connected instead of contact 11, the reversing contact Y being operated instead of contactor X, Y connecting the motor to the main (+ L). The current passes through the

armature in the opposite direction and reverses the rotation.

To prevent an excessive rush of current due to the controller drum being rapidly brought from the full-on position for one direction of rotation of the motor to the reverse rotation, resistances R_3 and R_2 and contacts P are fitted to the reverser and contacts 28 and 29 are fitted to the change-over contactors X and Y and act in the following manner :—

If the motor is running light the reverser SR remains in the mid-position, there being insufficient current in coil J to be effective. The current through the armature must therefore pass through resistances R_3 and R_2 instead of through the series winding.

These latter are adjusted to limit the rush of current to a particular value when starting up the motor without the series winding.

Contacts P are disconnected, so that the operating coil K of contactor M does not function and the circuit through the diverter resistance R is broken.

If the motor is loaded, the reverser is in one of the extreme positions and one of the contacts P makes circuit to the operating coil K of contactor M, but when the reverser changes over, these contacts are broken and M opens during the change-over.

The coils 25 and 26 of change-over contactors X and Y are connected to the main (+ L) through contacts 18 and 19 so that the circuit to these coils is broken if both X and Y are operating together. Therefore the contactor which is breaking circuit from main (— L) must connect to main (+ L) before the other contactor can operate to make circuit to main (— L). This gives a delay action during the change-over.

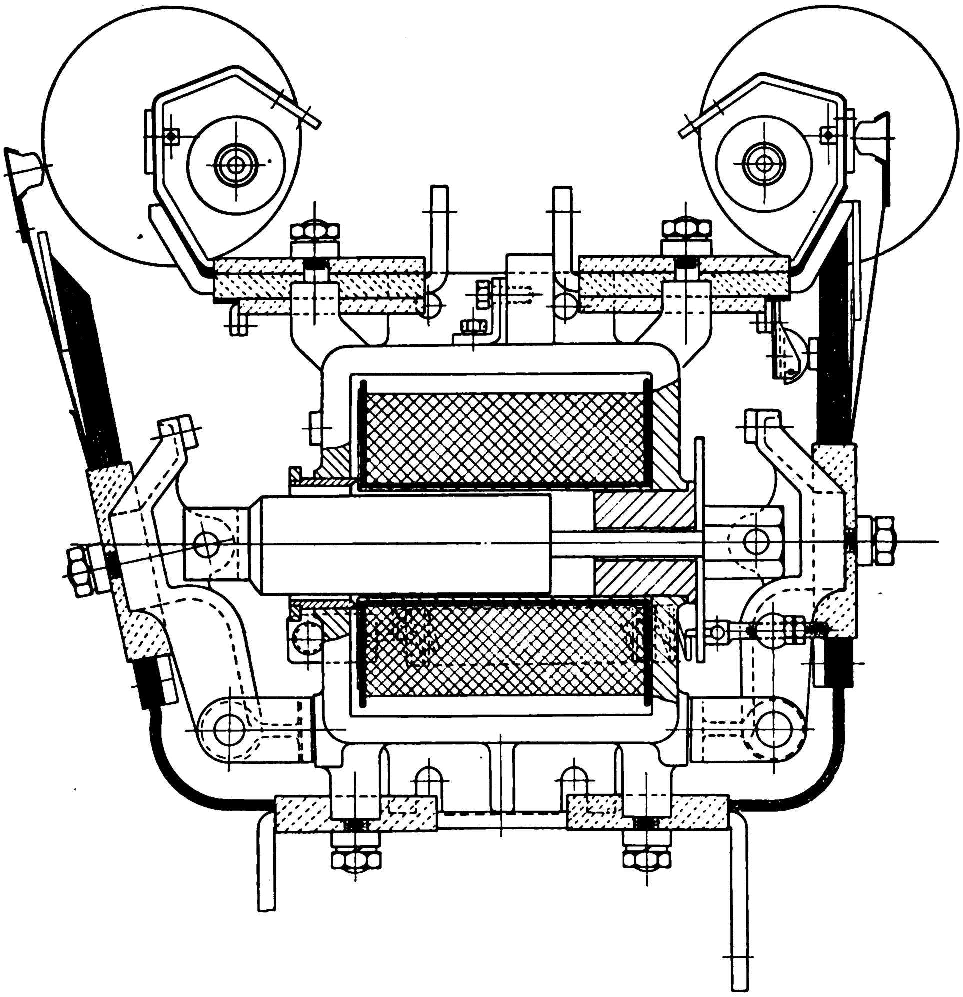

Fig. 10.

Excess voltage.—If the voltage fails and the motor is generating, through being driven by the load, then when the voltage across it rises above the line voltage by a prearranged amount the relay core 7 lifts and breaks contacts 6, disconnecting the circuit to the operating coils 25 and 26, and contactors X and Y make connection to the same main (+ L). The armature is now connected across the series winding and acts as a generator, keeping the load under control.

If the voltage fails under any conditions, relay coil S is de-energized and the core 9 disconnects and breaks its own circuit. This circuit is made again only by returning the master-controller drum to the "off" position W, making contacts 23 and 24.

The speed curves obtained from this arrangement are given in Fig. 8.

The difference between the hoisting and the lowering speeds is due to the difference between the voltages while generating and motoring, caused by the copper losses in the machine.

The advantages of the method of control here described may be recapitulated as follows :—

The efficiency of the system is high, since power is returned to the line when lowering the load, and the small gear reduction employed decreases the mechanical losses.

Low speed for taking up slack in the cable is obtained without losses in resistances.

In tests made upon a winch designed to lift 4 tons at 80 ft. per min., using this system, an overall efficiency of 65 per cent at full load was obtained. The efficiency remains comparatively high down to about one-quarter full load.

Stresses in the mechanical parts are reduced to a minimum since the angular momentum of the rotating armature is comparatively low, and the duration of an overload is made shorter by the insertion of an overload device in the mechanical, instead of the electrical, side of the machine.

The load is lowered under full control at predetermined speeds, without the wear and tear of a mechanical brake, and, when hoisting, the use of such a brake to prevent the load from running back is avoided.

The speeds obtained at light and medium loads are higher with a given size of motor, and the speed range is not limited by the characteristic of the machine.

The rates of acceleration and retardation are unusually high, full lowering speed being quickly attained by the application of power, until regenerative speed is reached, while the load is promptly checked and landed carefully and without damage.

The copper losses in the motor being heavy, the current is low when the machine is stalled.

The figures and curves given in the paper were obtained during tests made upon ships' deck winches designed to lift 4 tons at 80 ft. per min., the gear ratio employed between the armature and the lifting barrel being 4 to 1. The motor was without interpoles, 12 main poles being fitted, and was designed to run at 52 r.p.m. when lifting 4 tons at full speed.

The apparatus used in obtaining the curves shown in Fig. 8 was purely of an experimental nature. This particularly applies to the reverser then employed.

The special contactors used are shown in Figs. 9 and 10.

With regard to the comparative costs of the high- and low-speed types of motor, it must be considered that although that of the low-speed motor taken alone is excessive, the fact that the motor is embodied in the winch, the absence of magnetic brake, etc., and the reduction in the cost of mechanical parts and protective appliances, make the arrangement competitive for a given duty and rating. It is also open to question whether the low-speed machine for intermittent duty cannot be more highly rated for equal reliability since, for instance, the short-circuit current is lower and the motor is thus less likely to be stressed through ill-usage.

The author has found that the duty of a crane or winch seldom bears any relation to the rating specified for the motor, and he suggests that the specification should give the required temperature-rise for a duty of so many tons to be transhipped a given distance in a stated number of hours.

As the reliability of a low-speed motor is only limited by the permissible temperature-rise, the duty it has to perform should be more closely considered and the limit of temperature-rise more closely approached under working conditions.

THE PROPAGATION OF RADIO WAVES.

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[From the National Physical Laboratory; communicated by permission of the Radio Research Board.]

(*Paper first received* 23*rd October, and in final form* 24*th December*, 1925; *read before the* WIRELESS SECTION 3*rd February*, 1926.)

SUMMARY.

The paper gives the results obtained from a systematic study of the received intensities of various long-wave transmitting stations at four receiving stations over a period of nearly two years.

The weekly averages of the results are studied, and it is shown that they are inconsistent with any law of steady decay. The results also show very marked periodic variations.

It is suggested that all the observed effects can most easily be explained on the assumption of an upper refracting layer. This is supported by the results obtained from plotting an intensity distance curve in detail by means of a portable set, and by the study of the systematic changes which take place daily during the sunset period.

Various conclusions are drawn from these results, but it is pointed out that considerable further experimental investigation of many of the observed phenomena is necessary.

INTRODUCTION.

The study of the propagation of radio waves through the space between the transmitting and receiving aerials is one that has attracted many workers, as it is of fundamental importance. Ever since the early days the discrepancies between actual and expected results have demanded explanation. The problem has often been attacked from the theoretical side; but in those days, largely owing to the limitations of experimental technique, the underlying physical data were indefinite, and consequently very varying results were obtained. With the development of the thermionic valve and the resulting more accurate measuring apparatus, however, it has become possible to put the experimental side on a firmer basis and so provide more definite information for the theoretical solution.

Even from the experimental side there are two ways of approaching the subject, though the line of demarcation is not always sharply defined.

The first is primarily concerned with obtaining data for reception and transmission purposes; and so is most concerned with long-distance transmission under working conditions. Valuable theoretical results may, and do, follow from this, but they still remain a secondary factor. On the other hand immediate practical results may be subordinated, the measurements being viewed chiefly as a convenient means of examining the electrical state of the intervening medium, in which case it often happens that the actual figures obtained have no direct practical application. In the following work the second of these two alternatives has always been given most consideration, and consequently, after the first preliminary trials, all experiments have been chosen with a view to illustrating some particular feature to the best possible advantage.

APPARATUS.

The apparatus is substantially the same as that described in a previous paper,* the only considerable alteration being the substitution of a Dye transformer † for the calibrated mutual inductance. Actual experience has, of course, resulted in a certain number of detail modifications both in design and in operation, the chief one being the addition of a string galvanometer so that readings can be taken on the ordinary routine of a station; but the fundamental principle remains unchanged.

GENERAL PRINCIPLES.

This series of experiments differs from the majority of those which have already been made on this subject in several important particulars. The chief of these are:—

(*a*) Distances are comparatively short.
(*b*) Simultaneous observations have been taken whenever possible.
(*c*) Only daylight transmissions have been considered.

As these are not accidental, but part of a settled policy, they require a short consideration.

Experiments of this nature differ from many others in containing an excessive number of unknown and uncontrollable factors. In the first case, many of the causes of variations are at present altogether unknown, and the experimenter has practically no power of controlling them, or even of being able to repeat an experiment under reasonably similar conditions. Secondly, although on ideal grounds the transmitting station should be under his control or, as in the case of the special "URSI" signals, be working under carefully observed conditions, it is in practice impossible to extend this to all the observations which become necessary; so that, even in the case of the known possible causes of variation, the control is still incomplete.

Scientifically, this means that the number of independent variables is unusually large; so that unless the routine of observation is controlled as rigidly as possible, masses of results are obtained under such indeterminate conditions that, except on a purely statistical basis, no attempt can be made to sort out the various causes. In the early days of the work this rule was, of course, less rigidly applied, but as soon as an inkling into possible causes had been obtained, subsequent experiments were planned to illustrate that particular point under the most favourable conditions.

* *Journal I.E.E.*, 1923, vol. 61, p. 501.
† *Ibid.*, 1925, vol. 63, p. 597.

It is not denied that the results of long-distance work are in practice the most important and yield the most surprising results. They are also the ones to which most attention has been given by other experimenters, so that a considerable amount of information is already available about them. If, however, the matter be considered in the same light as any other physical experiment, the natural method is to take the simplest cases first, and to work up from them to the more complex. After all, the mechanism of propagation must always be the same, though it may exhibit its effects differently at different distances.

Comparatively short-distance work appears to offer an opportunity for reducing the uncertainty with regard to some of these independent variables, as it seems reasonable to suppose that there is a chance of natural phenomena being more constant over small areas than over large ones. In particular, it removes the special cause of difficulty in long-distance transmission in which the path contains both day and night sections. It also tends to higher accuracy of measurement, owing to the more powerful signals in relation to disturbances.

It appears very doubtful whether any satisfactory generalizations can be drawn from measurements of a single transmitting station at a single receiving station. Such a process assumes that the situation of the receiver is ideal and unaffected by local conditions, and also that the law of propagation is perfectly regular and uniform, and it offers no verification of either of these facts. Consequently, in these experiments four receiving stations have been used, at Slough, Manchester, Glasgow and Aberdeen. These sites had to be chosen more with a view to the facilities available than on scientific grounds, but the results obtained seem to justify their choice.

Experimental Results.

The basis of all the earlier work has been the "URSI" signals. These are special transmissions arranged under the auspices of the Union Radio Scientifique Internationale, and consist of a preliminary call—URSI de . . . .—then a statement of the exact wave-length and aerial current of the previous day's transmission, followed by a steady dash lasting two minutes. Those of which most use has been made are :—

(i) From GBL (Leafield) daily except Sundays and public holidays at 1400 G.M.T.; $\lambda = 12\,350$ m; $I = 200\ a$ (nominal).

(ii) From UA (Nantes) daily at 1415 G.M.T.; $\lambda = 9\,000$ m; $I = 180\ a$.

(iii) From LCM (Stavanger) daily at 1000 G.M.T.; $\lambda = 12\,140$ m; $I = 200\ a$. (In this case the signal consists of a series of 20-second dashes.)

A signal is also sent from LY (Bordeaux) at 1955 G.M.T.; $\lambda = 18\,900$ m; $I = 480$; but this has not been much used up to the present, owing to its proximity to the sunset period.

Routine observations have been kept on these stations since June or July 1924 and, in the case of Nantes, at Manchester since March 1924. Slight interruptions have been caused at times owing to the fact that to obtain trustworthy results it is vital to employ competent experimenters, who, in general, could only give part of their time to the work.

These results have been sent to Teddington, where they are reduced to a fixed aerial current and then each set is averaged weekly. The system of weekly averages, each involving, as it does, from two to six readings only, was adopted after some consideration, as it was felt that they were rather small groups to average.

The plotting of daily results was soon found to be too cumbrous, whereas monthly averages would have enormously lengthened the work, and might possibly have hidden interesting transient results of shorter period. On the whole, the study of the curves seems to show that the system of weekly averages has been fairly justified.

The results require analysis on both a time and a space basis, i.e. a study of the week-by-week variations at each receiving station of each transmitter, and also of its simultaneous distribution at all four receiving stations. In view of the number of graphs involved, and the widely different scales to which they have to be plotted, it is necessary at times to plot selections from them in various fashions, but for the present all results will be derived from the weekly figures referred to above.

Seasonal Intensity Graphs.

Fig. 1 gives the weekly averages of the observations on Nantes and Leafield at the four receiving stations over the period June 1924–December 1925.

Considering first the early months, the most striking feature is that Manchester recorded, on Nantes, signals equal to and even greater than those at Slough, although the distances are 695 km and 485 km. It was also noticed that, on the few individual days when variations did occur, they usually appeared at all stations, but not necessarily in the same direction. An unusually high value at one station was generally accompanied by a low value elsewhere.

During September 1924, although the change in weekly averages was mostly small, day-to-day variations became much larger; and at the same time it was noticed at Slough, where simultaneous readings of direction were taken on another set, that the bearings were becoming unsteady and the minima poor. In October, however, big changes began to occur, culminating in the sudden and enormous variations in the week 25th October–1st November. Consideration of the daily logs shows that actually the majority of the changes occurred between the 27th and 30th October, and, as it was really this which gave the first suggestion of a possible cause, it requires discussion in detail.

The first, and most striking, characteristic was the simultaneity of the changes. In these few days signals from stations as far apart as Nantes and Stavanger, at receivers as far apart as Aberdeen and Meudon, showed abrupt changes, amounting in some cases to over 100 per cent, and the figures published by Prof. Mesny in *L'Onde Electrique* of readings on Bordeaux at Meudon show the same variation (see Fig. 2), even though at this time of year this signal is sent several hours after dark. Traces of the effect are also visible in Dr. Austin's

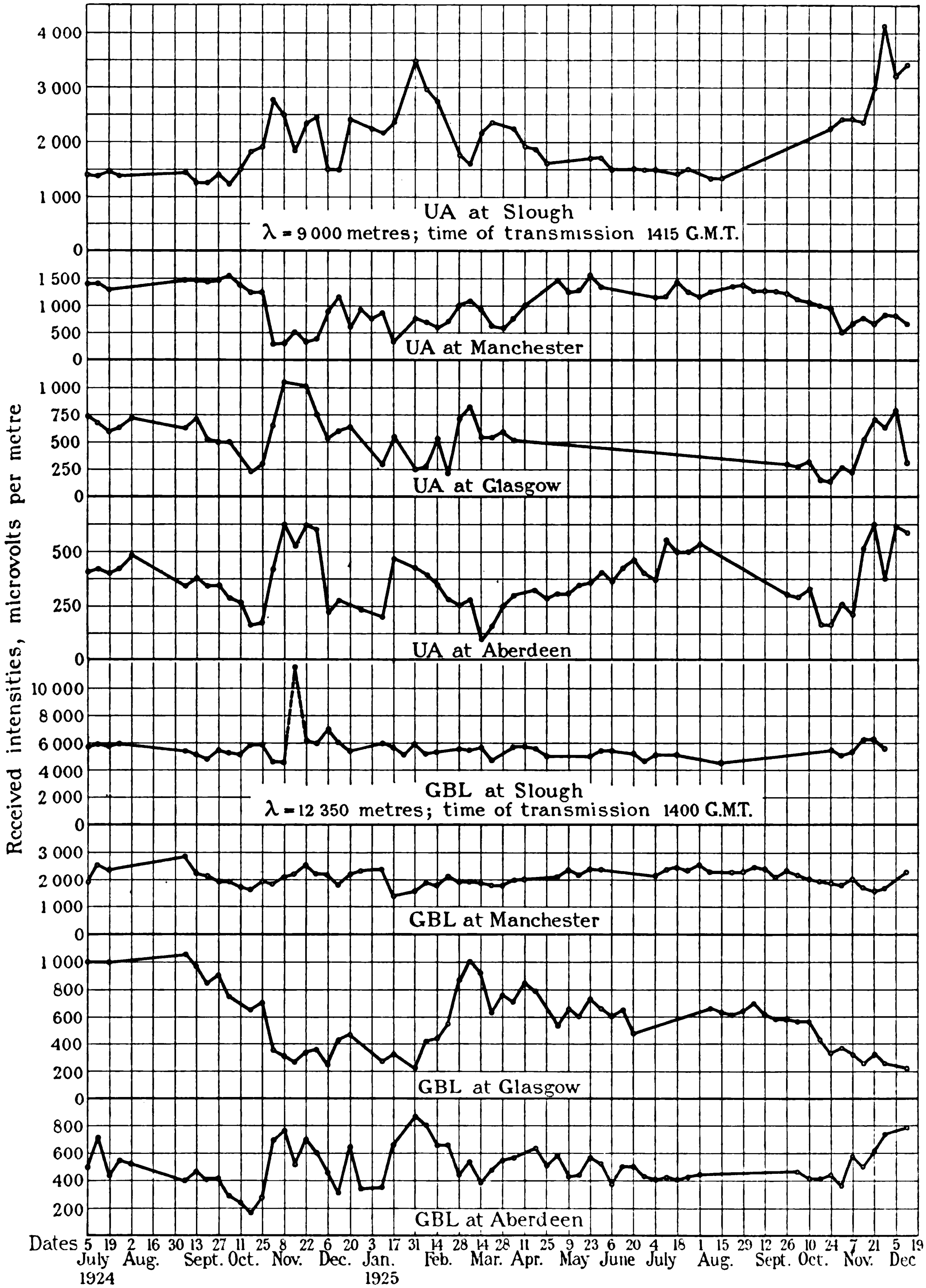

FIG. 1.—Diagram showing weekly average intensities of "URSI" signals from UA (Nantes) and GBL (Leafield) at the four fixed receiving stations.

figures for observations on some of the European stations at Washington,* and in a recent paper by Captain Round and Mr. T. L. Eckersley † Fig. 14 seems to indicate a similar phenomenon in previous years, though the exact time of its occurrence is not so definitely marked. The effects were not merely transient, as in most cases, although the day-to-day unsteadiness was very marked; there was in the following weeks no definite reversion to the summer values.

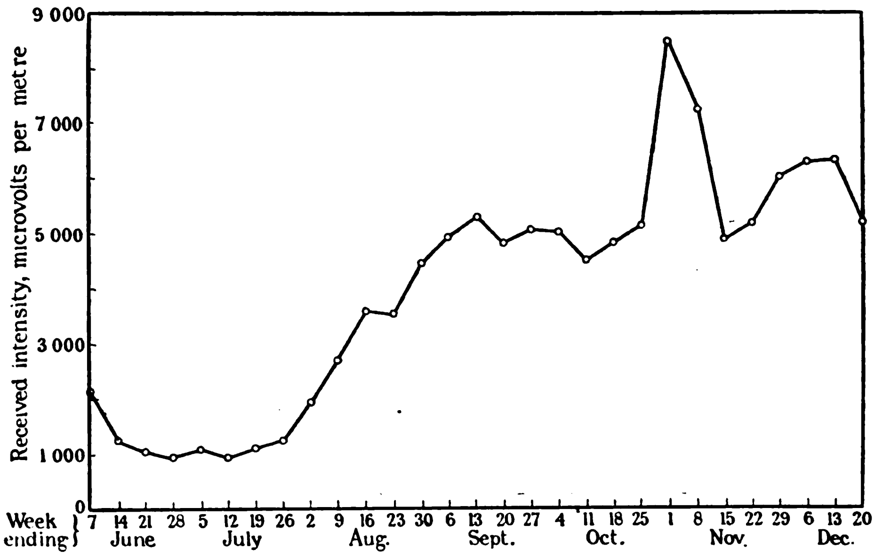

FIG. 2.—Weekly average of "URSI" signal from Bordeaux (LY) received at Meudon by Prof. Mesny. $\lambda = 1\,920$ m; time 1955 G.M.T.; distance, 520 km.

In 1925 the results were very closely similar, in that, during the spring, signals gradually steadied down again to practically the same values as those during the previous summer. In the autumn the same feature

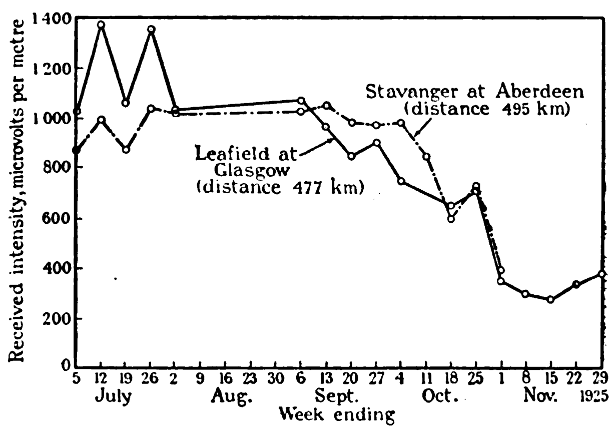

FIG. 3.

of the abrupt October change again occurred on practically the same days. Another fact, perhaps equally striking, is that after this date the day-to-day variations were enormously greater than before it.

* *Journal of the Washington Academy of Sciences*, vol. 15, p. 227.
† *Journal I.E.E.*, 1925, vol. 63, p. 943.

For instance, in the week ending 29th November, 1925, the daily readings of Nantes at Manchester were 1 320, 1 390, 50, 209, 550; and at Aberdeen 560, 500, 241, 115, so that with results like this a weekly average figure has not much meaning. This will be referred to later.

It is hardly possible to avoid the conclusion that these changes were not due to local variations, but to some main cause operative over a large area, and the possibility is also suggested that all signal-strength variations might be due to this cause, differing in degree rather than in kind. Also, in view of the fact that the signals from Leafield at Glasgow and from Stavanger at Aberdeen (see Fig. 3) were practically equal, although the

TABLE 1.

Distances between Transmitters and Receivers.

	Slough	Manchester	Glasgow	Aberdeen
	km	km	km	km
Nantes (UA) ..	485	695	973	1 100
Leafield (GBL) ..	78	184	477	590
Stavanger (LCM) ..	911	775	680	495
Northolt (GKC) ..	13	243	540	630
St. Assise (FT) ..	396	635	930	1 000

former path is entirely over land and the latter entirely over sea, it does not seem possible to admit the conductivity of the ground as a major controlling factor. It seems most unlikely that this conductivity should remain constant for over four months, and then change suddenly and completely in two days, especially as it will be remembered that 1924 was an extremely wet year, and there are no signs of permanent weather change about this date. Also, Smith-Rose and Barfield

have shown * that in the British Isles, at any rate, the conductivity of the soil for long wave-lengths is of a high order.

Further, it will be noticed that at times during the 1924 winter period the intensity of the signals from Nantes at Manchester is actually less than that at Glasgow and Aberdeen, whereas in the case of Leafield the Aberdeen figures are above the Glasgow figures. The various distances are given in Table 1.

For medium distances, therefore, it seems that there is no justification for holding to any law of steady decay except for purely practical average purposes, because to explain the above figures on such a basis, modified by purely local conditions at each station, would involve a large number of simultaneous and elaborate but totally independent coincidences.

It remains to be seen if all these effects can be approximately accounted for by a single cause.

Intensity/Distance Distribution.

To discuss this it is necessary to make use of space-distribution curves, i.e. to plot intensity against distance and not against time. Such a curve is given

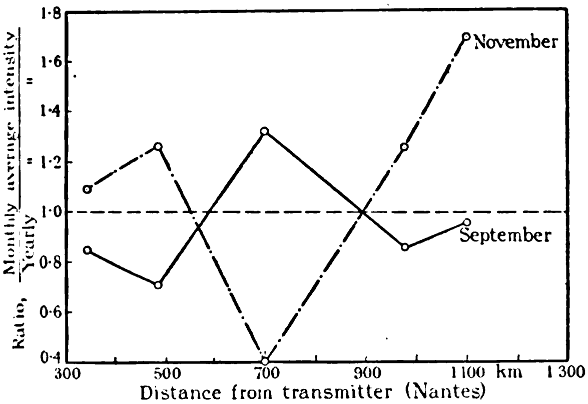

Fig. 4.

in Fig. 4, but the ordinate scale is unlike the previous ones owing to the fact that, due to the ordinary attenuation, the actual intensities at the various stations are widely different. For the moment we are more interested in the relative variations than in the absolute values, consequently the ordinates in Fig. 4 are the ratio of the monthly average intensity at any point to the mean annual intensity at that point. By this means the relative changes at each station can be studied on a common scale. As at the moment it is the change during October which is under consideration, the two curves in Fig. 4 are derived from the monthly averages in September and November. The September curve is closely similar to those of the preceding months and may be taken to represent the average summer distribution ; October is deliberately omitted, being treated as a transition period. The characteristic features of these curves are clearly the alternation of high and low values, and also the complete reversal of form between the two months.

Curves of this nature at once suggest something in the nature of an interference phenomenon, so that from this point the primary object of subsequent experiments has been to study this effect under the most favourable conditions.

Now if, as suggested by this and previous results, the intensity/distance distribution is not a smooth curve, it follows immediately that a very much larger number of points on it are required than can possibly be obtained from the four fixed stations ; so it was decided to proceed immediately with the construction of a portable measuring set, and meanwhile to carry on with the steady routine of " URSI " signals with a view to their future interpretation.

A study of Fig. 1, and more especially of the daily logs, shows that for an experiment of this nature, which would inevitably occupy some weeks, the work could only be done at a period of the year at which the day-to-day consistency was highest. This limits the possible period to from the middle of May until the middle of September, and consequently the early months of 1925 were occupied in the development and construction of the portable set. The work gained added interest about this time from the publication of an article by Prof. Appleton and Mr. Barnett,* suggesting the existence of a similar phenomenon on shorter waves ; but unfortunately their experimental method was not practicable in the case of long-wave high-power stations. Various delays intervened, and finally it was impossible to start work with the portable set before the middle of June.

Although the original ideas had been derived from measurements of the signals from Leafield and Nantes, neither of these stations was quite suitable for the purpose of this later experiment. In the case of Nantes, its working hours are short and irregular, and for this sort of work it is vital to have a station working practically continuously, as when on tour it is impossible to guarantee arrival at a fixed spot at a fixed time. The geographical situation of Leafield is also not altogether satisfactory, as an inspection of the figures already obtained suggested that the phenomenon would not in this case become strongly marked until the north of Scotland was reached, which would involve an excessive amount of travelling, together with a possibility of not being able to extend the tour far enough away from the station to obtain the required result. Choice finally fell on St. Assise (FT ; $\lambda = 14\,350$ m). This station appears to work almost continuously during the most suitable observing hours (10 a.m. to 4 p.m.) and it gives a powerful signal, which is most convenient since the limitations involved in making a set portable lead to a slight sacrifice of sensitivity and accuracy. Preliminary tests also showed that the signal usually maintained a very steady value throughout each period of working.

Moreover, reports from the fixed observing stations during May showed that, whilst it was well received at Glasgow and Aberdeen, considerable difficulty was experienced with it in Manchester, where signals were, on an average, only about one-third of the strength of those at Aberdeen. It was thought that either this was a very marked case of interference, or that

* *Proceedings of the Royal Society*, A, 1925, vol. 107, p. 587.

* *Nature*, 1925, vol. 115, p. 333.

Manchester conditions were abnormal, so that a tour on this station might enable a definite decision to be reached.

Five tours were therefore made, four being confined to working as nearly as geographical conditions would permit on the great circle from FT to Aberdeen, and one with the definite object of getting as far away from this great circle as possible, in order to see whether the effects were confined to any particular direction. During these tours control observations were kept at one, at least, of the fixed stations.

In an experiment of this nature, besides the question of day-to-day consistency, there is also the factor of suitable sites, as, especially in hilly country, the choice of what appears to be an ideal position for a site is not always available. Of the actual sites on which the readings were obtained, some did certainly appear to be very good, being situated in open country free from steep hills, heavily wooded country, or long-distance telegraph lines. Such good sites were obtained, in particular, on Salisbury Plain, on Dartmoor, and in the neighbourhood of Nottingham. Examination of the curve shows, however, that the readings obtained on these sites are not appreciably nearer to the mean curve than some taken in what at first sight appeared to be far less satisfactory positions.

In one particular case a reading was taken just at the top of a steep drop, in what was practically a Devonshire lane, the hedges on the side banks being above the level of the top of the coil and the lower wires below the surrounding ground level, but the reading was quite normal. The question of long-distance telegraph wires is a more open one, as it is conceivable that their effect may be dependent on the constants of the circuits, in which case immunity from trouble is merely a matter of luck.

All readings were taken at a distance of not less than 200 yards from such wires.

The results are shown in Fig. 5, and the small sketch map (Fig. 6) gives an indication of the points at which observations were taken, the difference in the bearing of FT at the extreme points being 42°. After allowing for all the factors mentioned above, the curves appear to be very definite and to be entirely free from anything in the nature of a steady decay, the dotted line being the theoretical value as calculated from the Austin-Cohen formula. This curve is given, as there is reason to think that, whilst the authors of it fully appreciate the limitations under which it is applicable, some subsequent writers have invested it with an accuracy and validity which were never originally claimed for it and seem entirely unjustified. The curves seem to justify very definitely the claim for the existence of an interference phenomenon and, owing to the greater number of points on them, allow conclusions to be drawn with a much higher degree of certainty than when observations were confined to the fixed stations.

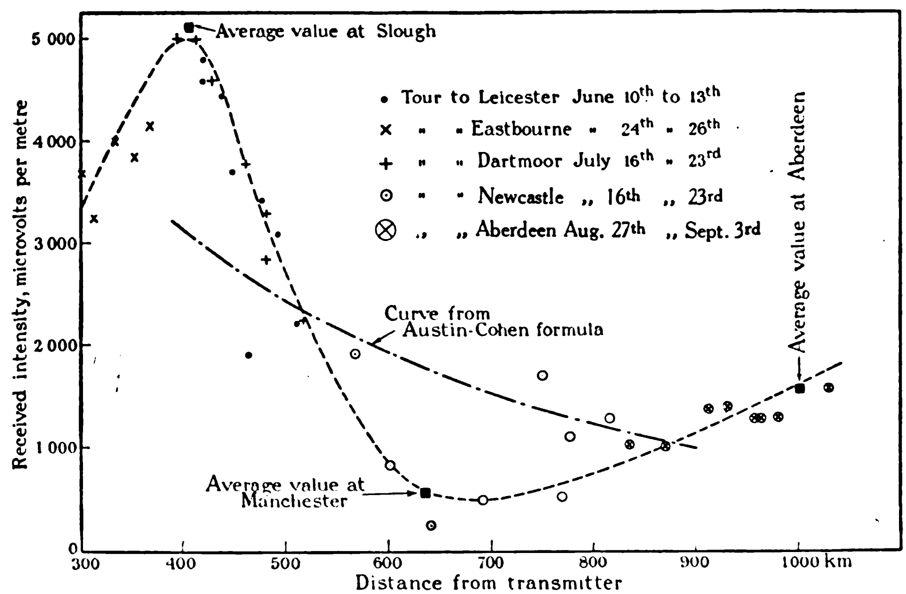

FIG. 5.—Intensity/distance curve during summer months taken on St. Assise (FT; 14 350 m) in 1925 with a portable set.

General Inferences from these Results.

In view of the fact that hardly any two of the points at which readings were taken lay exactly on the same great circle through the transmitter, it seems unlikely that these effects are confined to any particular direction. Also, the various paths contained very different proportions of sea and land, which again goes to confirm the view expressed earlier in the paper, that for these wave-lengths the nature of the path is of minor importance.

An interference phenomenon demands two waves, so that it is necessary to give a short discussion of the means by which such two waves could arise. In some of Sommerfeld's original work it is shown that the

velocity of propagation of a "surface" wave over a semi-conductive layer is slightly different from that of a "free" wave in space. At first sight this suggests a possible explanation of the phase-changes necessary to produce an interference effect, but calculation shows that by the time a sufficient phase-change had occurred due to this cause, the "surface" wave would have been attenuated to a negligible intensity. It seems, therefore, that the explanation must be found rather in difference of path length than in velocity of propagation, and this leads at once to the idea of the upper layer. The existence of such a layer has been suggested from the earliest times, and forms the basis of most of the mathematical work on the subject; but opinion on this point is by no means unanimous, and it has been claimed that all observed phenomena can be accounted for without its assistance.

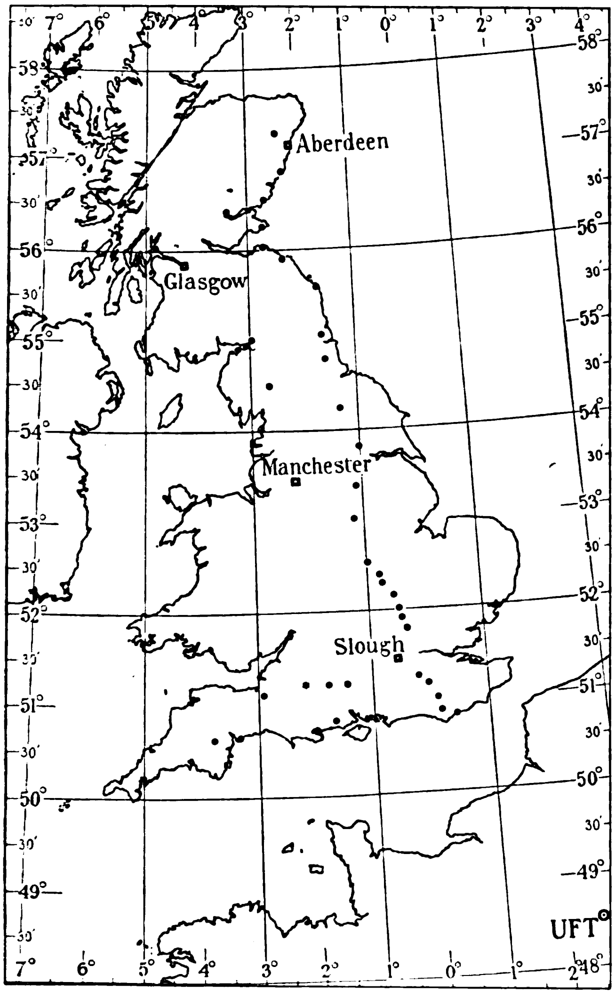

FIG. 6.

It is therefore proposed to assume as a starting point the existence of such a layer, but with its characteristics unspecified, and then to show that all the results obtained in the paper can be accounted for if certain definite constants are attributed to it. The question, by its very nature, does not permit of direct experiment, but can only be settled by the accumulation of evidence.

Now if on the surface of the earth (Fig. 7) one wave follows the arc A B between the two stations, whilst another is reflected at a point C on the upper surface, it is easy to calculate the phase-change due to the difference of the paths A B and A C B. At this stage of the work it is impossible to give a decision as to the actual physical nature of the layer, its constitution, or its sharpness of definition, the layer in Fig. 7 being treated as the imaginary sharp layer required to produce the same effect. Consequently, it cannot be said definitely whether the effect is strictly one of refraction or reflection, or, as seems likely, something of an intermediate nature. In all that follows, the word "refraction" is used in this indeterminate sense and must not be more strictly interpreted. Many more experiments under varying conditions are required before this further question can be answered in detail.

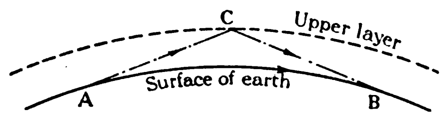

FIG. 7.—Diagram illustrating wave paths.

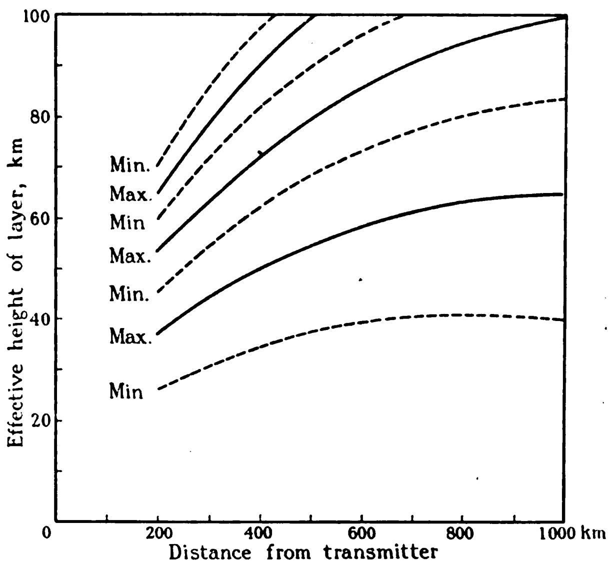

FIG. 8.—Chart of position of interference phenomena for $\lambda = 14{\cdot}35$ km.

Returning, however, to Fig. 7, the distances at which maxima and minima should occur for various heights of layer have been calculated for the wave-length of FT ($\lambda = 14\,350$ m) and are plotted in Fig. 8. The full lines give the positions of the maxima, and the dotted lines the minima.

With regard to these curves, it is very important to note that the actual positions of the maxima and minima are independent of the attenuation of either of the waves, a fact which is of great value, as it eliminates some of the most uncertain of the unknown factors. The actual intensities at these points are, however,

entirely dependent on the attenuations, so that the interference phenomena will exhibit all degrees of intensity. At short distances, where the surface wave is strong and the refracted wave weak due to the small angle of incidence, the maxima and minima will follow in rapid succession as the distance varies; but their actual excursions will probably be so small as not to be definitely separable from the irregular momentary and daily variations. As the distance from the transmitter increases, the effects will become more and more marked and, as appears from Fig. 5, an almost total extinction may be obtained; whilst at greater distances, due to the large attenuation of the surface wave, the effect will again diminish, if by this time it has not totally disappeared, as the last minimum will of course be at the point at which the two paths differ by half a wave-length. Thus, to exhibit this effect to the best possible advantage, the distances from the transmitter must be carefully chosen or it may be overlooked.

Now, if Fig. 5 be compared with Fig. 8, it will be seen that the conditions are fairly well satisfied if the equivalent height of the layer be taken as 75 km, which should give a maximum at 430 km, and a minimum at 640 km, with no intermediate value.

Returning for the moment to Fig. 4, if its figures are compared with graphs of the same type as Fig. 8 but drawn for the appropriate wave-length it will be found that, for the September reading, a layer at a height of 72 km should give a minimum at a distance of 450 km and a maximum at 800 km. These correspond very fairly to Fig. 4, after making allowance for the fact that with only four points of observation the position of the maxima and minima cannot be determined to any high degree of accuracy. The November reading in Fig. 4, on the other hand, suggests a height of the order of 85 km. It thus appears that, at any rate up to this date, all the major elaborate variations observed are explicable on the assumption of a refracting layer at a height of about 75 km during the summer months, rising somewhat abruptly during October to a height of about 90 km.

This does not, of course, definitely prove the existence of such a layer, as any other theory which could account for the observed results would be equally acceptable; and all that can be said at present is that it offers what appears to be the simplest explanation, which, at the same time, covers all the most marked observed phenomena.

Of the actual physical nature of the layer, present results are not sufficient to give any details. General conceptions are somewhat adverse to the idea of a sharply defined surface of separation, though it must be remembered that sharpness would only be a relative term, being in fact a function of the wave-length; so that the degree of sharpness may be entirely different for long and short waves, with a resulting difference of observed phenomena. If, however, the suggestions put forward by Dr. Eccles * or Prof. Larmor † are accepted, the practical result is that the "effective height" would be different for different wave-lengths. The range of wave-lengths used in this paper is not sufficient to settle this point without special experiments designed to illustrate it, but it is hoped to undertake these in the future.

* *Proceedings of the Royal Society*, A, 1912, vol. 87, p. 79.
† *Philosophical Magazine*, 1924, vol. 48, p. 1025.

Seasonal Variations.

So far, results have been chiefly confined to the summer period. The next points arising are :—

(i) Comparison of results obtained during the summer and winter months.
(ii) Comparison of results during the same period in successive years.

The abrupt transition at the end of October appears to mark a distinct line between these two periods, and in this connection also the curve given in Fig. 2 is of special importance. It is obtained from the results published periodically by Prof. Mesny in *L'Onde Electrique*, and its significance lies in the fact that the time of transmission (1955 G.M.T.) is close to the sunset period. Actually it is about the time of sunset at Bordeaux on the longest day, and at Paris in the middle of July. The first rise in the curve evidently corresponds to the normal sunset change, which is discussed in more detail below, but the striking point is that, after a comparatively steady period following this, another abrupt change occurs at exactly the same time as on the stations whose transmissions are in daylight throughout the year. As by this time of year sunset has occurred, both at Meudon and Bordeaux, several hours before the reading is taken, it seems impossible to argue that the winter change is merely a reversion to normal night conditions. The two may be related, and probably are, but they do not seem to be identical.

For the daylight stations the results appear to group themselves into two sections, that from May to September being marked by its relative stability, and that from October to May both by average values differing largely from the summer ones, and also by a very pronounced day-to-day instability.

Also, it has been shown that the marked change at the end of October is consistent with a rise in height of the layer from 75 to 90 km, so that it seems natural to suggest that some, at any rate, of the winter variations are due to the same cause. Unfortunately, the large day-to-day variations referred to above cause great difficulty in applying the system of weekly averages, which under these circumstances do not appear to possess much physical value. For this purpose a daily analysis of the results has been undertaken, in order to see if even the daily variations will allow of quantitative explanation, but the preliminary arithmetical work is very heavy and it is not possible to say yet whether the analysis will be successful.

One point in connection with the layer appears to be very striking. It is clear from Fig. 8 that a change in height of only about 10 km may be sufficient to convert the signal at a given point from a maximum to a minimum. Now the readings during the summer show that the day-to-day variations at any given point are often only a few per cent, and that even the weekly average for the same week in successive years may not differ by more than this amount. Consequently, although it appears that the layer undergoes a nightly change, it must go through a cyclic change of extraordinary

constancy over periods measured by weeks if not by months. It may be added that it is admittedly somewhat premature to draw conclusions as to yearly variations from observations extending over so short a period.

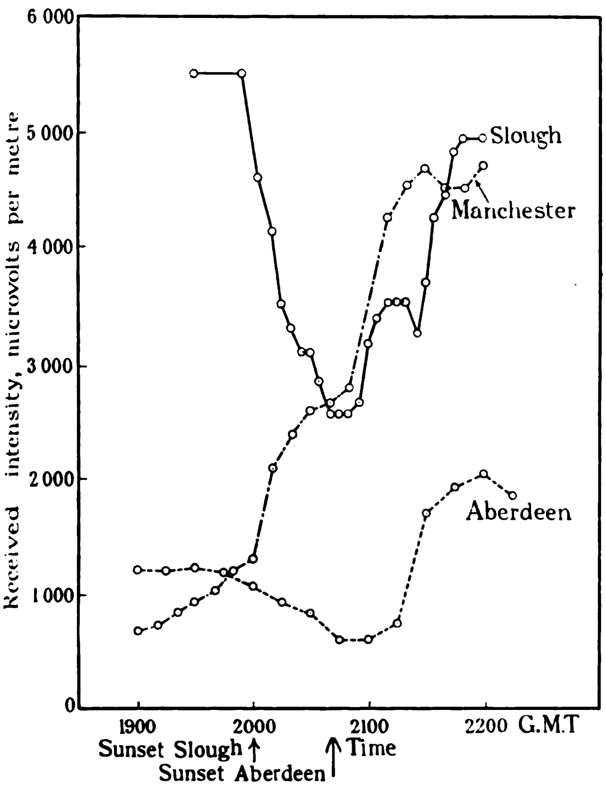

FIG. 9.—Sunset run on St. Assise (FT ; 14 350 m), 21 July, 1925.

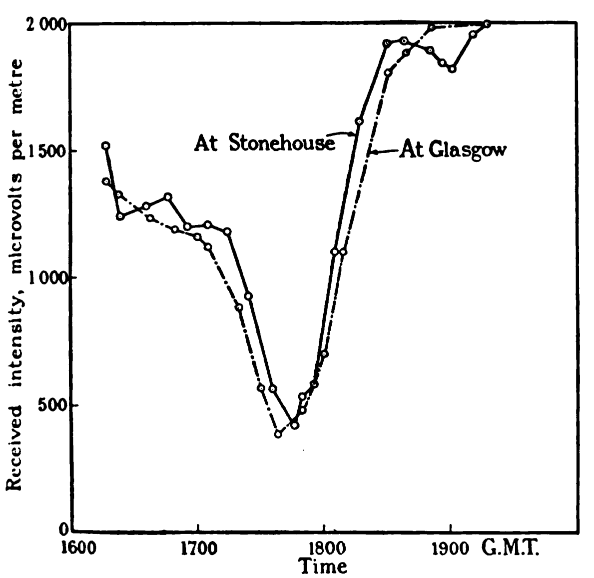

FIG. 10.—Sunset run on FT (St. Assise) on 12 October, 1925. Stations 24 km apart.

Time alone can settle this question, but it is certainly striking that, as far as results go at present, there appear to be very marked signs of an annual repetition.

SUNSET EFFECTS.

A completely separate series of experiments suggested by my assistant Mr. Naismith have also been made. Continuous watch kept at Slough during the summer months on St. Assise from about one hour before sunset until two hours after, showed that during the summer period the intensity went through a very marked cycle of change, which was repeated daily with only very minor modifications. Similar observations were therefore organized at the other three permanent stations, and the results showed that whilst the same

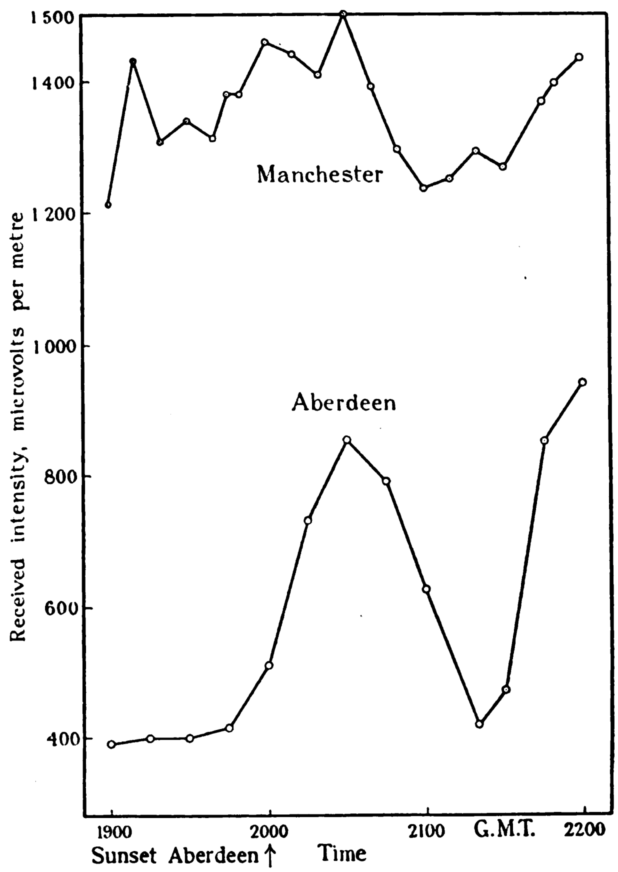

FIG. 11.—Sunset run on Northolt (GKC ; 6 950 m), 30 July, 1925.

thing was true at every station, the actual curves obtained had entirely distinctive and different shapes. These are given in Fig. 9 for FT at Slough, Manchester and Aberdeen, and in Fig. 11 for GKC (Northolt) at Manchester and Aberdeen. Fig. 10 is also interesting, as showing the curves obtained at the same time by two independent stations 24 km apart. Neither of the observers knew that the other was working, and the results obtained have been plotted without correction, so that it would appear that the agreement between the various sets of apparatus is good. It will be seen at once from these curves that the effect can no longer be classed under the general heading of "night increase," but that it must be, although perfectly systematic, of a much more complex nature. Now it is generally

held by the supporters of an upper-layer theory that, with the removal of sunlight, the effective height of the layer increases.

Following out this idea, if the curves in Fig. 9 are compared with the graphs in Fig. 8 the variations at all stations are explicable on the basis of a rise in effective height from 75 km to 90 km, bearing in mind the fact which has been referred to above, that a minimum is not necessarily a zero.

Another interesting, though tentative, calculation can be made from these results. From Fig. 9 it is possible to determine the actual values of the maximum or minimum attained at each station, and sometimes both, depending on the range of the curves.

The intensity of the diffracted wave can also be calculated from the formula given by Watson ‡ and by Van der Pol,§ and hence the intensity of the reflected wave is known.

From this the equivalent reflecting power of the layer can be deduced, on the assumption that the intervening air is a perfect dielectric.

The figures actually obtained are shown in Table 2.

Table 2.

	St. Assise (FT ; λ = 14 350 m)			
	At Slough	At Manchester	At Glasgow	At Aberdeen
(i) Maximum value from curve	*	*	*	2 000
(ii) Minimum value from curve	2 500	600	400	600
(iii) Calculated surface wave..	4 000	1 980	1 000	900
(iv) Reflected wave	750	1 300	700	750
(v) Calculated maximum value	5 500	4 600	2 800	2 100
(vi) Reflection coefficient†	0·16	0·42	0·37	0·42
(vii) Angle of incidence on upper layer	68·5°	75·5°	78·5°	79·5°

A corresponding figure derived from the Northolt results is 0·6 for the reflection coefficient, but it must be remembered that the idea of working out these results only occurred some time later. It has consequently been necessary to assume the nominal value of aerial current, and if this was not the actual value when the observation was taken the reflection coefficient would be correspondingly different; in fact, further work suggests that this figure should also be of the order of 0·4.

These results are interesting, especially as showing the rapid falling off of reflecting power for larger angles of incidence, which is not altogether unexpected, but like many other figures in the paper they must only be taken as provisional and subject to further verification, by the method of daily analysis referred to previously.

Conclusions from the Results.

Whilst many of the ideas suggested in this paper cannot at present be regarded as much more than guesses at a possible state of affairs, it may be as well to collect and re-state some of the definite facts that rest on experimental evidence and must form a basis for any theory which can cover them.

(1) Long-wave signal intensities over medium distances (< 1 200 km) remain extremely steady over the period May to September, during daylight hours.

(2) Their distribution does not correspond to the Austin-Cohen formula for anything less than yearly averages, in which case the distance is not large (see Table 3) and the law of decay is not uniform.

Table 3.

	UA		GBL	
	Yearly average	Austin-Cohen value	Yearly average	Austin-Cohen value
Slough ..	1 880	1 660	5 560	5 650
Manchester ..	1 070	1 040	2 100	2 260
Glasgow ..	690	650	820	770
Aberdeen ..	370	530	510	590

(3) During the sunset period each station goes through a distinct and individual cycle of change, which is repeated daily.

(4) Towards the end of October all observed stations showed simultaneous and large departures from their summer values. This is the beginning of a period of marked day-to-day instability, which persists until the following May, by which time all stations have settled down to their normal summer values.

* It is not always possible to determine these values reliably from the curves. For instance, in the case of a V-shaped curve such as that for Slough (Fig. 9) there is no definite evidence of a point of inflexion having been reached either at the beginning or end. The missing values have therefore been calculated in (v) in order to see whether they are of the right order, and they appear to be in most cases very close to figures which have at times been obtained (cf. Fig. 5 for the maximum value at Slough).

† The reflecting power of the ground has been taken as unity, as Dr. Smith-Rose's results (in course of publication) have shown that this is not far from the actual figure.

‡ *Proceedings of the Royal Society*, A, 1919, vol. 95, p. 83.

§ *Philosophical Magazine*, 1919, vol. 38, p. 365.

(5) Careful plotting of a day-time intensity/distance graph gave an undulating curve, showing, under certain conditions, practical extinction at a definite distance.

(6) In addition to the slow periodic changes, there appear to be more rapid fluctuations superimposed. During the summer months they are comparatively small, but assume big intensities during the winter. There is not yet evidence to decide whether these are due to fluctuations of layer height too small and rapid to be definitely detected by present methods, or whether they are due to some totally separate cause.

Extension to Long Distances and Short Waves.

The actual results in this paper are definitely confined to medium distances and long waves, as the deliberate idea throughout has been to investigate phenomena rather than results ; but at the same time it is interesting to inquire how the ideas can be applied to these other cases.

(*a*) *Long distances.*—The interference phenomena discussed above have a definite upper limit of distance for two reasons. The first is that, on the assumption that they are caused between a refracted and a diffracted wave, the attenuation of the latter is so large that at great distances its effect is negligible. Secondly, these effects cease when the difference in path length for the two waves becomes less than half a wave-length ; and this, together with the curvature of the earth, places a definite geometrical limit on the possible distance, there being also a maximum range for a first reflection with a given height of layer.

The idea of multiple reflection cannot, however, be excluded (cf. Captain Round and Mr. Eckersley *) and it is conceivable that some effect of the following nature may take place.

The signal from a distant station would consist of the vector sum of a series of multiple reflections. The least number of reflections possible is given by dividing the total distance by the maximum range of a single reflection leaving the earth tangentially (in the case of a layer 75 km high this figure is 1 950) and taking the next integer above this.

* *Journal I.E.E.*, 1925, vol. 63, p. 995.

Theoretically all multiple refractions of a higher order than this would be present, forming an infinite series, but actually, owing to the loss at each refraction and the gradually increasing angle of incidence, their relative attenuations would be rapid and probably only two or three would survive to a measurable extent. These might even show interference phenomena among themselves, though at large distances the effect would be so sensitive to variations in the layer too small to produce any effect at short distances that it would for practical purposes be incalculable.

(*b*) *Short waves.*—There is danger in applying these results directly to wave-lengths below 1 000 metres, for, whilst the presence of such a suggested upper layer would be a very important factor in short-wave propagation, the difference in frequency is so great that there is no doubt but that the actual observed phenomena would be entirely different.

Conclusion.

In conclusion, it is again well to lay emphasis on the fact that, whilst the results given in the paper are reasonably definite, the conclusions drawn from them must not be treated as more than suggestions with varying degrees of validity. The primary object has been to deduce from somewhat general observations definite systematic points requiring further investigation, and it is not until confirmation, or the reverse, is obtained that any opinion can be expressed as to the degree of actuality of the suggested phenomena.

This work was carried out for the Radio Research Board under the Department of Scientific and Industrial Research, and I am indebted to the Committee on Propagation of Waves for their helpful criticism. Finally, I must express my gratitude to the observers at my out-stations, Dr. Fyvie at Aberdeen, Mr. Hoyle at Manchester, and Messrs. Dalgleish and Naismith at Glasgow, the latter of whom is now working with me at Slough since the departure of my previous assistant Mr. Reading. To them has fallen the part of taking the routine, and somewhat monotonous, observations, without which none of the results could have been obtained.

Discussion before the Wireless Section, 3 February, 1926.

Prof. E. W. Marchant: The variations that the author has observed in the winter months are just about the same as those we observed in Liverpool on (UA) and Nauen during the winter months of 1924. I feel considerable doubt, as indeed the author himself does, as to the value of the weekly averages which one obtains by taking means with results of that kind. The suggestion that the author makes—that these variations are all explained by interference phenomena—is, I think, open to criticism. There are some days in the winter when nearly all stations seem to come in very much more strongly than they do on other days. I should like to ask whether it is possible to get any evidence of interference bands from those who have made observations of signal strength on board ship. Austin has done a good deal of work on that subject, and other workers in this country have also made many observations. It would be interesting to find out whether these observers, when they made accurate measurement of signal strength, have observed variations of the same kind as those the author has noticed. The most interesting figure in the paper is Fig. 5, which shows the up-and-down variation in strength as the distance from the transmitting station increases. It appears to give very clear evidence of the existence of interference bands and thus provides further proof of the existence of the Heaviside layer. It would have been of value if the author had included in this paper, besides

the weekly averages, the daily figures that were obtained at the various stations—Manchester, Glasgow, Slough and Aberdeen—so as to make it possible to estimate roughly the height of the Heaviside layer and the variations in height from day to day. In one respect our observations have differed from those which the author has described. We have found, in the relatively small number of observations we have taken, that there is not a constant effect from day to day at sunset. These results were described in a paper read before the Institution in 1915.* These experiments give clear evidence of interference and mark a definite advance in our knowledge of the causes of the variations which have been observed in signal strength.

Dr. E. H. Rayner : It will be seen from the account of the observations given in the paper that the sensitivity of measurement is not unlikely to be better than the sensitivity or accuracy of some types of ammeter by which the current is measured in transmitting antennæ. Absolute accuracy of indication of such instruments is of comparatively little importance at present, from the point of view of measurements described in the paper, but variation of accuracy is of real importance, whether it be a variation from hour to hour or month to month. There is also the difficulty as to what is the effective transmitting current when observations are made on traffic transmission by observing the amplitude of the excursion of a string galvanometer. It may be the same as is indicated by an ammeter, when a 2-second or 2-minute signal is sent, but it is also possibly somewhat different. Experiments have now reached a stage in which the performance of particular instruments, of a type the verification of which is a matter of considerable difficulty, has become one of the uncertain factors in work of this character. The difficulties are increased by their being situated in foreign countries in several cases. Prof. Marchant mentioned the subject of transmission to or from a ship at sea. This has seriously been considered by the Committee of the Radio Board. The suggestion was made that certain ships, on the Atlantic for instance, might be asked to send suitable signals for measurement on shore, or that shore signals should be sent for measurement on ships. The difficulties in connection with measurements of a physical character would, however, be very considerable. The effect of the ship itself, its rigging and the difficulty of assigning a reasonably accurate value to the effective height of its antenna, complicated by probable directional effects, seemed to make the numerical value of any observations obtainable so doubtful that it was decided not to carry the suggestion any further. Measurements made on a substantially metal-free ship offer a very attractive method of working, and it is hoped that some day an opportunity may arise of carrying out observations in such a manner. Since the subject of carrying out systematic observations at sea was considered, the land journeys have been made by the author, and have resulted in much of the information which it was the aim of the proposed sea observations to provide.

Mr. T. L. Eckersley : Particular interest seems to be associated with the November effect which was noticed by Capt. Round over long-distance transmissions as early as 1911. It seems to be a fairly universal effect. It was measured by us * and is shown in Fig. 142 (page 943 of vol. 63) and it was suggested on page 983 that this effect over great distances was partly due to an increase in height of the layer, but chiefly to an increase in attenuation. The author, by confining his attention to relatively short-distance transmissions, has been able in my opinion to separate these two effects, since attenuation has very little effect at such short distances and the major part of the changes must be attributed to variations in height. I am glad to note that he agrees with us in supposing an increase in height in the winter months. The fact that at short distances the November period does not show up as a sharp drop, but may be accompanied by a rise, suggests that the main cause in the drop in signals over long distances is increased attenuation. In confirmation of this we have a very distinctive evidence in the case of very short waves which indicate a *decrease* of attenuation in winter, thus implying an increase of attenuation in the winter daytime on the long wave. The chief interest in the paper seems to centre round the experiments, the results of which are exhibited in Fig. 5 and which seem to show up beyond doubt an interference pattern near the transmitter which we may very reasonably attribute to the interference of the ray reflected from the Heaviside layer with that diffracted round the earth's surface. The results are very remarkable as showing how far from a gradual decrease of signal strength with distance the actual signals are. Traces of the same effect are exhibited in Fig. 89 of our paper, showing the ratio of calculated to observed values of the signal E.M.F. over distances as great as 4 000 to 5 000 km, and were noted in our original measurement of signals from the American stations in England. Sine-wave deviations from the exponential decrease showed up in practically all our plots of the attenuation curves. The chief difference is that at the shorter distances examined by the author the maxima and minima are much more pronounced than those at greater distances. He has interpreted this result—I think quite rightly—as being caused by the interference of the direct and reflected ray from the Heaviside layer, and has used the observed results to obtain a tentative value for the height of the layer. I am not sure, however, that I quite agree with his numerical interpretation of Fig. 5. The estimated height is given as about 72 km, on the strength of the agreement of the maxima and minima with those shown in his theoretical diagram. I am inclined to think that the absolute positions of the maximum and minima are not so important as their distance apart. The absolute positions will be modified by any change of phase in reflection or refraction, which may amount to a considerable fraction of 180°, but the relative position should be independent of this to the first approximation. To obtain the best estimate the values at the shortest distances should be used where complications due to multiple reflection are least likely to occur. Taking these effects all into account I should estimate from the rapidity with which the maxima

* *Journal I.E.E.*, 1915 vol. 53, p. 334.

* "Report on Measurements made on Signal Strength at Great Distances during 1922 and 1923 by an Expedition sent to Australia," *Journal I.E.E.*, 1925, vol. 63, p. 933.

and minima alternate in the neighbourhood of 300 to 500 km that the height was not above 50 km, which is more in agreement with the results previously obtained by me by an independent method. These were approximately 40 to 48 km in the summer and 56 km in the winter. The discrepancy cannot be due to wave-length difference, as the results obtained by the author were on a 15-km wave, and mine in the range between 10 and 25 km.

Mr. J. E. Taylor: So far as the author's observations and the methods used in making them are concerned, there is little that can be fairly criticized. Such measurements are all to the good, though I fail to see how any prolonged scheme of observations can be planned out without having preconceived ideas of what is happening, and I imagine that is the case here. As far as the inferences drawn from the observations are concerned, qualified though they may be, I wish to express my entire disagreement with the author, and also to take special exception to the scanty treatment of what I call the guided-wave view. It is dismissed in a few words by reference to Sommerfield's surface-wave effects or theory. I look upon that part of the paper with some suspicion as an attempt to drag a red herring across the trail. Has the author ever heard of waves on wires; does he realize that those waves follow the wires with the strictest fidelity through all their bends and turns and twists? Does he realize that those waves do not necessarily decay to a negligible intensity after traversing hundreds and even thousands of miles? Would it make any difference to those waves if instead of a long wire we make them travel along a broad strip of metal, or if instead of along a broad strip of metal we make them travel along a sheet of metal? Will not they still follow the curvature of that metal without the assistance of any hypothetical upper reflecting layer? Very well. Suppose we cover the earth with that sheet of metal; surely the waves will still follow its curvature. Then remove the sheet of metal from the surface of the earth. Why will not the conducting surface of the earth still guide the waves? That is the robust proposition the author will have to face—not Sommerfeld's theory of surface waves. Now, on that view, how are we to explain this interference phenomenon? In my view the author is dealing with two sets of waves, one transmitted direct from the transmitting station to the receiver, wherever it may be, over the great circle of the earth, and the other set of waves going completely round the earth, which re-concentrates as it gets back again and interferes with the direct wave. The interference would, of course, depend simply on the arrival phase of the waves transmitted completely round the earth. That is my opinion, and I feel quite strongly on the matter. I cannot help suggesting that a good deal of time, money and energy is being wasted on the pursuit of this academic myth of a useful ionized layer.

Dr. R. L. Smith-Rose: The results shown in Fig. 5 give, I think, what is a new view as to the propagation of waves, namely that under stable daylight conditions the signal-strength/distance curve passes through a series of maximum and minimum values and does not show a steady decay as we have all hitherto thought was the case. In the latter portion of the paper the author deals with an explanation of these results on the basis of a reflected wave from the upper atmosphere interfering with the direct waves along the earth's surface. To some of us, before we heard Mr. Taylor speak, this evidence was convincing enough in itself, but I should like to draw attention to the fact that a much larger amount of evidence exists at the present time than has been given by the present author, and this, I think, affords adequate confirmation of the theory. Others beside Mr. Taylor have been sceptical about the existence of the Heaviside layer. If any excuse were needed for that scepticism I would say that it has provided the incentive for several years' experiments which have now brought quite fruitful results. Several investigators who have been associated with the Radio Research Board have obtained other evidence on this matter. In a paper read before the Royal Society last December, Dr. Appleton and Mr. Barnett described the measurement of interference effects between reflected waves and direct waves on the earth's surface, somewhat similar to the author's work but on shorter wave-lengths. In addition, another method was described there of which it is difficult to give any other explanation than that of a wave coming down on the earth's surface at an appreciable angle of incidence. Mr. Barfield and I have been engaged for two years in trying to convince ourselves whether this explanation of variations in signal strength and in bearings is correctly ascribed to waves reflected from the upper portions of the earth's atmosphere. We have now developed four different methods of determining that waves do at night come down on the earth's surface at an appreciable angle of incidence. Those four methods are absolutely independent of each other and can be worked independently by independent observers, yet they give very similar results. Three of those four methods enable us to measure the actual angle of incidence at which the wave comes down on the earth's surface, and also the relative intensity of the direct and down-coming waves. It is well known from fundamental classical theory that if an electromagnetic wave is sent through space the wave is constituted by an electric force and a magnetic force at right angles to each other and to the direction of propagation. It is also fundamental that these two forces are exactly equal to each other at all times anywhere in the line of propagation. If, therefore, waves are received at any part of the earth's surface horizontally, such as I understand is the case with the so-called guided-wave theory, those two forces must be equal at all times. Using methods by means of which the electric force and the magnetic force can be measured independently, it can be shown that at night under certain conditions where we get variations in signal strength and bearings the magnetic force is frequently greater than the electric force. That might appear to be a rather startling result, but there is a perfectly simple explanation of it. If a wave comes downwards and not horizontally, immediately it hits the earth's surface (the earth being a tolerably good conductor) a reflected wave will be set up. In such a case it can be shown that the ratio of the magnitude of the resultant vertical electric force to that of the resultant horizontal magnetic force is equal to the sine

of the angle of incidence of the arriving wave, and will thus be less than unity. The very fact that at times the resultant fields are not equal is considered to be a definite proof that a wave is coming down on the earth's surface at an angle of incidence which is not 90°, i.e. it is not arriving tangentially as it would be by the guided-wave theory. If the wave is travelling along horizontally at the earth's surface, the magnetic force is horizontal. By measuring the direction of the magnetic force it can be proved quite definitely that its direction can depart from the horizontal under suitable conditions of night phenomena. This is considered to be a second proof that waves are coming down from the upper atmosphere and not being transmitted horizontally along the earth's surface. With regard to phenomena associated with direction-finding observations, I thought it might be interesting to set up a direction-finder and take bearings on the "URSI" signals simultaneously with the measurement of signal strength the author was carrying out, and on the lantern slide are shown graphs of the daily bearings observed on these signals sent by Leafield and Nantes. The observations extend from October 1924 to December 1925, and were all taken in daylight, the signals in question being sent at 2 p.m. and 2.15 p.m. It is seen that in the winter months—from October to March—the bearing varies from day to day over a range of 10° to 15° on either side of the true bearing. About March the bearings settled down, and during the whole of the summer months it was moderately steady—a small variation of 1° or 2° only, which may be due to slight instrumental error of the apparatus. In October the variations start in a similar manner to the previous year. In the case of Nantes the variations are similar, but not quite so large. These effects resemble the signal-strength variations which the author obtained at the same time; he found erratic variations during the winter months and steady results during the summer months. The author has explained that during the summer months his results still necessitate a reflected wave as well as a direct wave. Since the bearings are quite steady during those summer months, that reflected wave must have come down in such a manner that it could cause no variation in bearings, since we got negligible variations in the summer. That is, the polarization of that wave was always such that the electric force was in the vertical plane and the magnetic force in the horizontal plane, whereas during the winter months and at night time the plane of polarization of that reflected wave must have been rotated so that the magnetic force was no longer horizontal. That indicates a possibility of having a downcoming wave which is normally polarized, as we term it, and which is not rotated in its path and thereby does not cause any variation in bearing although it may result in variations in signal strength being observed. If those summer conditions indicate that the reflecting layer is at a lower limit of its height, then there would appear to be some minimum height at which rotation of polarization of reflected waves takes place. I notice that the author gives all his ordinates in microvolts per metre. As he is using a frame coil measuring horizontally the magnetic field and as, as has been pointed out, the vertical electric field is not necessarily equal to the horizontal magnetic field, he would not appear to be justified in giving the signal strength in microvolts per metre.

Mr. E. B. Moullin: I think that the time is not very far distant when we shall be able to correlate all these records and understand the conditions in which wireless waves travel, and also how these conditions change with season and wave-length. I regard this paper as a fund of useful information the significance of which we are not fully able to appreciate at present, and I read it with less thoughts of the present discussion than of its bearing on the discussion of some future paper. I think that Fig. 3 is very important, for it shows that waves of 12 km wave-length travel with equal facility over land or water: this conclusion seems final and we may accept it gratefully as at least one definite decision. I await eagerly a corresponding curve for a wave-length of say 600 m and then I expect we shall find that waves are transmitted much more readily over sea than over land. The suddenness of the October change does not impress me with the same force as it appears to impress the author. This change seems to me to have been in progress at all stations for a full month before the 30th October and to have continued long after; in addition the peaks and hollows at this time are not more violent than those which occur at other times in the year. I think that if the author had given more daily readings round about this time we might have been able to judge whether we should regard the end of October as a time when the average value changes very rapidly or whether to regard it as a time of great daily variation superposed on a slow change of the mean. I think that metereological and kindred records over this time should be searched in the expectation of finding also violent daily fluctuations of some observed quantity. The paper contains much confirmation of the hypothesis of a Heaviside layer and I think the analysis I am about to suggest might yield interesting results. If the layer exists, as it surely does, we are prepared to expect it at the same height over all the British Isles on any particular day. If this layer rises and falls regularly from year to year we should expect the season of maximum signals at one station to be a season of minimum signals at some other nearer or more distant station. If the curves of Figs. 1 and 2 were analysed into a Fourier series we should find how the phase of the fundamental variations was related to the distance from the transmitter. We could then test whether this phase change was consistent with a uniform height of layer and, if it were, we could find its rate of rise and fall. Casual inspection of Figs. 1 and 2 will show that the fundamental sine curve has a large amplitude and that the phase differs with the station; for example, Slough and Manchester are almost in antiphase with one another. In spite of the violent daily and seasonal variations, this paper discloses that the yearly average can be predicted very closely by the Austin-Cohen formula. This is very noteworthy and remarkable. Let us hope that time will prove this simple formula correct for the yearly average and then in course of time we shall be able to add to it a harmonic factor which will make the necessary seasonal variation which

arises from wave interference. If the Austin-Cohen factor is proved to be appropriate it will tell us much about the mechanism of attenuation. Now that this chain of observing stations is established we could obtain very valuable information if the transmitting station would alter its wave-length slowly and continuously for a period of an hour or so. This would virtually repeat the experiments of Appleton and Barnett with the advantage of several observing points. I hope that the author will put on record such explanations as he is able to suggest of the multiple-value points recorded in Fig. 5 and also state definitely the extreme range of variation recorded at the three watch stations during the time the trips were in progress. I think that analysis of the sunset effects might yield interesting information about the rate of rise of the layer during the sunset period. I notice that a string galvanometer was used to record the St. Assise signals, and I should like to know whether the mean recorded values depended on the rate of signalling. Though I realize that it is impracticable to publish the whole set of daily records, yet it would surely be an advantage if these should be accessible. I suggest that the Institution Library might keep a typed copy of the complete records. Possibly I do not fully understand Mr. Taylor's views respecting the mechanism of propagation round the globe, but surely it is a matter of common experience that if a source of light is placed close to the surface of a large opaque sphere, then no light is visible even a quadrant away from the source, an experience which is not modified appreciably by polishing the sphere.

Mr. P. P. Eckersley (*communicated*) : Qualitatively, undoubtedly, all must agree with the author's conclusions reached, whilst, as he himself has partly admitted, one may be more sceptical of the quantitative deductions. It is, perhaps, a little surprising to find no mention made, first, of a paper * recently read before the Institution by Mr. T. L. Eckersley, nor, secondly, of his previous papers published immediately after the war in the *Radio Review* dealing with work done from 1916–1918. These papers, I venture to state, anticipate a great deal of work done by others in the same field. I, for one, was satisfied by him in 1916 that theories of electric wave propagation, which sought to explain observed variabilities, must be based upon a reflecting layer hypothesis. If further confirmation of his original deductions is required, it is undoubtedly found in the interesting catalogue of observations contained in the present paper, and also in certain experiments conducted by Mr. Appleton and the British Broadcasting Company. The British Broadcasting Company have, by their unique opportunity of studying mass observation, obtained some interesting qualitative data on wave-lengths shorter than those observed by the author and his co-workers. Without doubt the "come down" of a station (i.e. the point B in Fig. 7) is manifest in broadcast telephony reception. In parts of Scotland, for instance, the Bournemouth station is louder than either Glasgow or Aberdeen. In many cases Scandinavian stations are louder than British stations, which are geographically less distant, and observers under the "arch of radiation" (the line ACB of Fig. 7) have frequently noticed a complete lack of correlation between signal strength and distance. Undoubtedly, at short waves (300 to 500 m) the effect of shielding by hills and mountains introduces other variables. In the valleys around Cardiff, and more particularly in the mountains near Milan, conditions *can* be obtained where even a sensitive receiving set is unable to pick up powerful stations a few tens of miles distant. A case is known of a particular fjord in Norway where a 7-valve supersonic receiver is, with an adequate aerial, unable at 10 miles from a 200-watt transmitting station to pick up even a heterodyne interference beat. In Britain, on the other hand, several hundreds of miles distant, the station, which incidentally is also severely screened, is clearly audible. One would suspect an accepted theory that the indirect ray is largely responsible for the achievement of communication. In further corroboration of the shielding effects by uneven ground, I have observed signals from London on the London–Daventry road, while travelling into the country, to be far weaker when descending the hills. Curiously, at every town the signal strength appeared to increase. The effects noted by indirect reception of screened transmitters are also noticed by transmitters which are unscreened and receivers which are screened. As a practical indication of this, I know of a case where two of the short-wave B.B.C. stations could be received quite adequately in a Norwegian fjord while 5XX, the long-wave, high-powered station of the B.B.C., was quite inaudible. Just outside the fjord 5XX came through roughly at the correct strength as compared with the short-wave stations. This would seem to point to the facts that the short-wave stations were being received on their indirect waves, the longer wave being not affected, in the same way, whereas outside the fjord the direct rays manifested themselves and, naturally, 5XX was the stronger. Further observations at very short ranges have been taken, and it has been observed that, where very strong signals obtain, a rough application of the inverse square law does not introduce serious errors. In broadcasting, those responsible for a satisfactory service are more interested in those areas where the signal strength is large compared with extraneous interference. In some tests on the so-called "crystal range" of a station (a scientifically ambiguous term signifying any range at which the signal strength is large compared with extraneous interference) between a set at Chelmsford using a power of 10 kW and another of 3 kW in the heart of London, the point of equality of signal strength was found to obey, within the limits of the inaccuracies obviously present, the inverse law. The place was, approximately, 8 miles from Oxford-street and 22 miles from Chelmsford. Other corroborations were obtained. In conclusion, I must argue with others that the value of the author's observations and his clear statement of fact cannot be overestimated, but he will without doubt forgive a healthy scepticism of the quantitative estimates derived on the basis of somewhat unconfirmed assumptions.

Mr. J. Hollingworth (*in reply*) : I agree with Prof. Marchant that it is necessary to accept weekly averages with reserve. I have in fact, discontinued taking them out during the winter, but during the summer I

* *Journal I.E.E.*, 1925, vol. 63, p. 933.

am inclined to regard them with more confidence. The alternative—the consideration of individual figures—involves very considerable reliance on instrumental accuracy, and on the constancy of conditions at the transmitting end. In the narrow sense, the statement that all effects may be due to interference phenomena is probably going too far and I would amend it to say that at these wave-lengths the majority of observed variations (especially at medium distances) are due to changes in the upper air rather than to surface conditions.

A daily analysis of results is now in progress and it is hoped to publish tentative results shortly, but the process is one of considerable difficulty and uncertainty, as in order to reduce anything to calculable form it is necessary to make certain arbitrary assumptions which can only be justified by the results they yield.

The daily results were not given in the paper, purely from considerations of space. My experience with the sunset results, which during last October were taken daily and are now taken weekly, is that occasionally the effect is definitely and entirely absent but when it does occur it always possesses its characteristic features. For instance, on the 10th February, 1926, the sunset curves at all stations were practically straight lines, whereas on the 17th February (the next observation) they reappeared in such marked form that the intensity at Aberdeen actually fell to zero for about 5 minutes.

I agree with Dr. Rayner that the reliability of the transmitting end is a factor of considerable importance as, even if accurate instruments were available, it is impossible to organize detailed observation of them over the very varying routines of observation which become necessary.

I agree with Mr. T. L. Eckersley that the most important feature about the November change is its universality, though I think its comparative abruptness is also striking. My personal experience of long-distance work is so small that I did not feel justified in doing more than merely comment on it, and I am indebted to him for his more authoritative opinion. I also agree that these sine-wave deviations from the smooth curve have often been observed before; they are in fact visible in some of Dr. Austin's original curves. In those very early days it is probable that instrumental uncertainties may have overshadowed them, and I think they have been usually treated as somewhat secondary phenomena, but the prime object of the present paper was to obtain them under the most favourable conditions and to use them as the fundamental analytical weapon.

The problem of the phase-change at refraction is a very vital one. It cannot be calculated directly until more information is available about the layer, which information is again itself probably most easily obtained from observations of this type, so that here, as throughout the work, it seems only possible to progress by a method of successive approximation. In the paper the mere path difference was taken as being the simplest assumption, though it was appreciated that the resultant "height" would be very artificial and that relative values would be of more value than absolute ones. Prof. Macdonald has since published a paper* in which it is suggested that under these conditions of working a constant phase-change of $\pi/12$ might be assumed, and the results have been recalculated on this basis. The effect on the height of the layer is small, lowering it 2 to 3 km at the utmost, but it does appear to give slightly more consistency in the daily analyses. It may be taken as the second stage of approximation. But even allowing for all these I find some difficulty in reducing the height to 50 km, for the following reason. In Fig. 5 we have a maximum at a distance of 420 km, followed by a minimum at 650 km. Now with the layer at a height of 50 km the phase-change of one wave relative to the other between these two distances due to path difference only is 46°. The angles of incidence on a layer at this height are respectively 76° and 81°. Consequently, if the phase-change at the upper surface in the first case is $\theta°$, the change in the second must be $(\theta + 134°)(= 180° - 46°)$, i.e. a change of only 5° in the angle of incidence must cause a variation in the refractive phase-change of as much as 134°. This of course is not impossible, but it seems very large to be assumed.

* *Proceedings of the Royal Society*, A, 1925, vol. 108, p. 52.

I am afraid I am unable to follow Mr. Taylor's ideas on guided waves from a quantitative point of view. Even if one were to admit his contention that such waves could travel very large distances along a pair of wires without serious attenuation (incidentally I believe Mr. Taylor admits that if his wires were perfect conductors they would not guide the waves, so that there must be some loss on this basis), I fail to see how the effect can continue when the wires are replaced by a conducting surface covering the earth, in which case the same amount of energy must spread out over the whole earth instead of being strictly localized as before. Again, with regard to the interference effect being produced by the reconcentration of waves which have travelled round the earth, the components of such a concentration, having all travelled by different paths, would meet with every possible value of relative phase relation and so would, on the whole, neutralize one another. Moreover, it seems inevitable that under such conditions the appearance of interference maxima and minima would be entirely fortuitous, whereas the experimental evidence alone, apart from any theory, shows that they obey very definite sequential laws. Moreover, Round and Eckersley have definitely observed a phenomenon of this type under antipodal conditions, the special features of which do not occur elsewhere.

There is not much that I can add to Dr. Smith-Rose's survey of the subject except to emphasize the point that this paper is simply another link in the chain of evidence. As he points out, at the time this work was started there were still very strong differences of opinion on the subject and in view of its importance there was a real need of further evidence gathered from as many different points of approach as possible. I have never regarded it as anything but a slightly new method of attack on an old problem, which is perhaps a partial explanation of the lack of references to other work that has been remarked upon.

The October change referred to by Mr. Moullin is probably of the nature of a sudden change superposed on a slow mean change, but I am at present inclined

to think that in a Fourier analysis the fundamental would be small. The striking fact is the abrupt change in the nature of the readings about this time, as will be seen from the figures in Table A.

TABLE A.

Readings of Nantes at Manchester (1925).

Average value for May,	1 334	Maximum value attained, 1 980.
„ „ July,	1 250	
„ „ Aug.,	1 310	Minimum value attained, 1 000.
„ „ Sept.,	1 220	(Each on one occasion.)

Daily Results for October and November.

Oct. 1	1 165	Oct. 30	85
„ 2	1 130	„ 31	390
„ 5	1 150	Nov. 2	110
„ 7	1 070	„ 3	285
„ 8	1 130	„ 4	73
„ 9	1 080	„ 5	1 300
„ 12	920	„ 6	1 150
„ 13	1 220	„ 9	1 300
„ 14	1 030	„ 10	835
„ 15	1 210	„ 11	270
„ 16	780	„ 18	750
„ 19	1 340	„ 19	77
„ 20	520	„ 20	1 365
„ 21	860	„ 24	550
„ 22	1 110	„ 25	210
„ 23	900	„ 26	1 390
„ 27	690	„ 27	1 320
„ 28	870	„ 30	1 310
„ 29	720		

It will thus be seen that on the 12th October occurs the first drop below 1 000 for nearly 6 months, and that on the 30th October the readings again broke abruptly to an entirely different order with enormous day-to-day variations. It will also be obvious from figures of this nature that any average taken during November would have no physical meaning.

The daily analysis curves also show a very abrupt change of height of 10 to 15 km at this time, but the change from comparatively steady to violent daily oscillation is the most marked feature. Probably the explanation may be found in a rapid change of layer characteristics in the neighbourhood of this height, and information on this subject from other sources would be extremely welcome.

The work of Appleton and Barnett was not specifically referred to since it was not actually published until after the completion of this paper, but the application of their method was seriously considered and only turned down for practical reasons. In their method the percentage variation of wave-length necessary to produce a given number of interference bands for small changes of wave-length is proportional to the wave-length. Hence on a wave-length of 9 000 m, the number of maxima obtained for the same swing of wave-length would be 1/20th of that on 450 m and is consequently mechanically impracticable. During the tour in Fig. 5 the extreme range of variations was about 20 per cent. These variations were not momentary, as during each day the variations were not more than 10 per cent, and it is thought that they were partly due to the seasonal drift as the tour extended over several months, and possibly also to slight differences in aerial current. It must be remembered that not more than 5 per cent accuracy is claimed for individual readings and perhaps 10 per cent on high-speed automatic working when using the portable set where it is not practicable to take so many precautions as on the fixed set. Provided the set is not worked with an excessively small decrement, there is no appreciable difference in intensity for any frequency of sending for which it is possible to observe the string movement with the eye. The station used, FT, which alternates periods of slow and fast sending, provided many opportunities of verifying this.

The double points in Fig. 5 are readings taken at different times and in different localities which happened to be equidistant from the transmitter. Some of them lie within the limits of experimental error, but the large variations at distances of 750 to 850 km cannot be explained on this basis. It is striking that they were all taken in the Northumberland district where the country is very broken (so that choice of suitable sites was extremely difficult) and where there is an enormous quantity of overhead lines of various natures. On the other hand they may be purely experimental errors. As every reading taken on the tours is included, the graph is not merely a selection of the best. The neighbourhood requires more survey to settle this point and this was not possible last year, but I am hoping to obtain this year, curves on the same lines as Fig. 5 but on different wave-lengths, and while I am in that district I shall investigate the point further.

I cannot understand Mr. P. P. Eckersley's remarks as to the absence of reference to Mr. T. L. Eckersley's paper. It is definitely referred to twice, though in the advance proofs of the paper (for brevity's sake) it is mentioned by the name of the first author (Captain Round) only. Personally I was never of two minds as to the value of this work, but is Mr. Eckersley aware that as late as the end of 1924 the definite statement, "There is no Heaviside layer," was made and several times repeated in a paper, and that a similar opinion has been expressed this evening? In view of this it appeared that there was still further need of independent evidence on the subject, and this paper has attempted to supply it in part.

The results obtained by B.B.C. stations are most valuable on this subject and I hope they may be followed by quantitative figures. They show that there is no doubt that shorter waves are affected by the configuration of the ground, and also probably by the nature of the surface. From the point of view, however, of the study of the upper layer such results would merely introduce a further complication into a subject already bristling with indeterminate factors, and I feel that for this investigation long waves are preferable to begin with. The study of shorter waves is, of course, an essential future development.

THE DIRECTIONAL RECORDING OF ATMOSPHERICS.

By R. A. WATSON WATT, B.Sc. (Eng.), Associate Member.

[Communicated by permission of the Radio Research Board.]

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SUMMARY.

The paper describes a simple pen-writing instrument for the continuous recording of the apparent direction of arrival of atmospherics, and cites typical samples of the data obtainable from such recorders. The samples chosen show the diurnal variation of intensity of atmospheric disturbance, the diurnal variation of apparent direction of arrival, and the location of apparent sources of atmospherics by a group of recorders.

TABLE OF CONTENTS.

I. INTRODUCTION.

The data which have until recently been available as to the incidence of atmospherics have consisted almost entirely of relatively brief and isolated observations based on aural estimates. There does not yet exist a sufficient quantity of comparable data, from well-spaced observing stations, over an adequate period, to present anything beyond the barest outline of the world distribution of atmospherics. The purpose of the present paper is to describe an instrument which, despite many limitations and imperfections to be enumerated, does enable continuous records taken under comparable conditions at widely distributed stations to be obtained and compared without an excessive expenditure of effort. The description is followed by some data from a first group of such recorders, which are presented as typical of the minimal results to be expected from an international network of co-ordinated recording stations. Such a network seems to be called for at the present stage of research on atmospherics.

II. HISTORICAL.

The development of the recorder to be described arose from a limited investigation into the possibility of locating thunderstorms by observations on the apparent direction of arrival of atmospherics, which was initiated by the Meteorological Office in 1915.* This work was subsequently developed into a fundamental inquiry into the origin and nature of atmospherics, under the auspices of the Radio Research Board which was established under the Department of Scientific and Industrial Research in 1920.

The first observations were made aurally by means of the standard Bellini-Tosi radiogoniometer, and the results of observations at certain coastal direction-finding stations have been discussed elsewhere.*

As a matter of convenience, recourse was later had, at the experimental station set up at Aldershot by the Meteorological Office, to the frame-aerial direction-finder, and a statistical analysis † of a year's data from this instrument has been published. While these observations were in progress, and in the intervals of other meteorological duties, experiments were in progress with a view to the development of a simple and easily operated directional recorder, with the purpose of obtaining data throughout the 24 hours, and not merely at selected hours. The obstacles to the production of such an instrument were, at the period when the work was undertaken, the lack of a robust pen-writing galvanometer of short period with good damping, and the imperfections and inconstancy of the multi-stage triode amplifier.

Many schemes for recording were considered and tried. It was known that for application to everyday meteorology a recorder depending on photographic registration would be unsuitable, hence the otherwise clearly indicated Einthoven galvanometer was ruled out. Considerable success had been attained with a modified Duddell oscillograph arrangement, carrying a light siphon pen in place of the mirror, when details became available of the Abraham-Bloch moving-iron oscillograph. The published data showed that this instrument had a sensitivity comparable with that of the bifilar instrument tried at Aldershot, and was considerably more compact and economical. Samples were therefore procured, and the form of recorder developed depends on the use of the Abraham-Bloch instrument.

Concurrently, tests were made of a variety of triode amplifiers, with special reference to their suitability as amplifiers of atmospherics. The special features required were stability and constancy, freedom from internally generated disturbances simulating atmospherics, and absence of sharp selectivity. The resistance-capacity type proved itself by far the most suitable.

* CAVE and WATT: *Quarterly Journal of the Royal Meteorological Society*, 1923 vol. 49, p. 35.

* WATSON WATT: *Philosophical Magazine*, 1923, vol. 45, p. 1010; *Nature*, 1922, vol. 110, p. 680; and *Journal of the Royal Aeronautical Society*, 1925, vol. 29, p. 62.

† WATSON WATT: *Proceedings of the Royal Society*, A, 1922, vol. 102, p. 464.

The first instrument resulting from these experiments came into operation at Aldershot in December 1921, and continued to run practically uninterruptedly until August 1924, when it was dismantled for removal to the new site at Ditton Park, near Slough, of the Radio Research Board's station for investigations on atmospherics.

Slight mechanical and electrical improvements, converting the instrument into a self-contained device ready for housing in an outer shell of the requisite size, were embodied in the pattern of recorder finally standardized, constructed at the Aldershot station and issued in 1924 to four stations at home and abroad. This standardized pattern of directional recorder for atmospherics will now be described in detail.

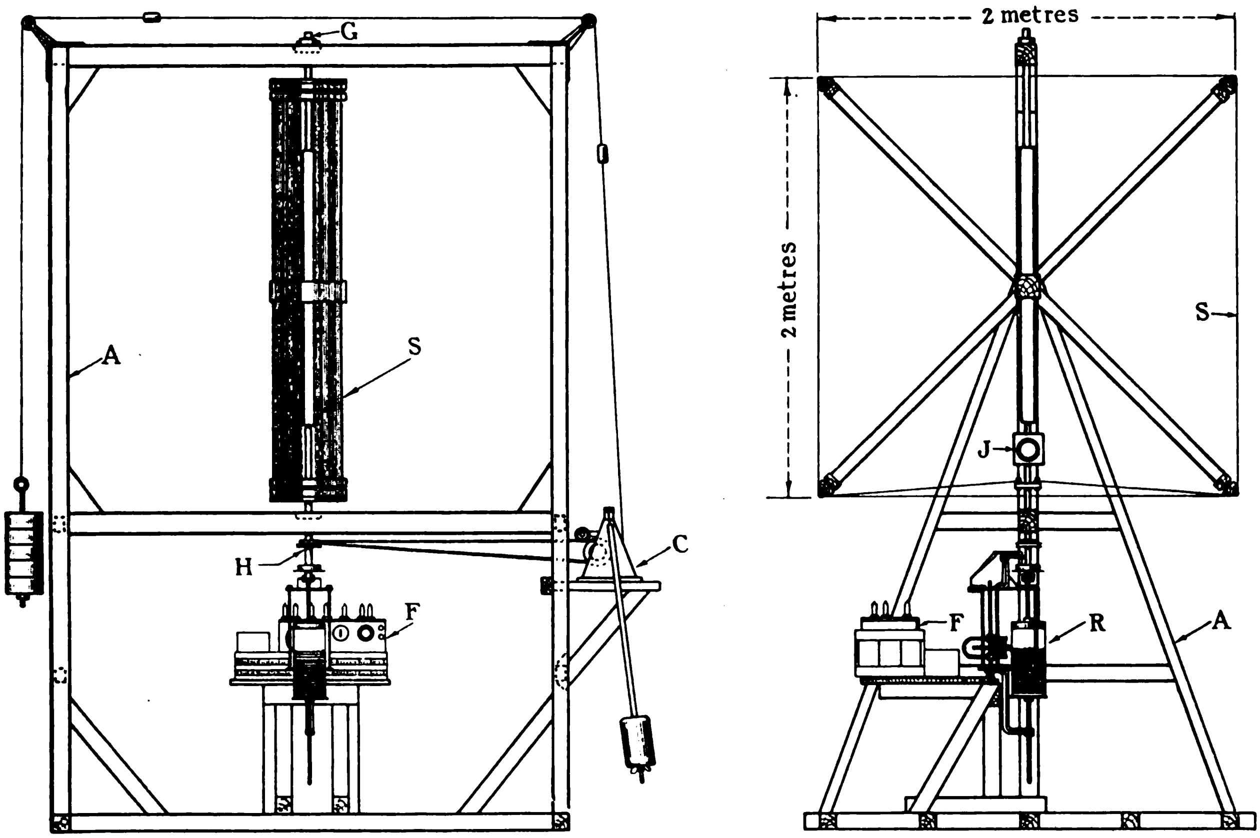

Fig. 1.—General arrangement of recorder.

III. The Directional Recorder.

The instrument, the general arrangement of which is indicated in Figs. 1 and 2, comprises a teak framing A, which supports a frame antenna S, belt-driven by a turret clock C, and carrying a recording drum R, on which is inscribed the trace of the oscillograph pen E, actuated by the output of the multi-stage amplifier F connected to the frame antenna.

The main teak framing is designed to give the rigidity required for smooth and uninterrupted running. Early experience showed that the reserve of driving power from a clock of moderate dimensions was so slight that rigid supports and careful maintenance of clean bearings were essential. The base measures approximately 2·5 by 2·2 metres, the overall height being just under 4 metres. The hut necessary to house the instrument, with the necessary clearances, measures 4·5 metres high by 3·75 metres square.

The driving clock, supported by a bracket on the outside of the main framing, is a small turret movement with a 15 cm (6 in.) main wheel and a robust escapement protected by a safety clutch. The driving barrel is exceptionally large; since daily winding at the time of chart changing is convenient a relatively small driving weight with a rapid rate of fall is permissible, and the weight of about 30 kg falls 7·5 cm per hour. The driving cable, broken by insulators, passes over pulleys which carry it over the main framework. This maintains the self-contained nature of the installation, and makes some slight contribution to the rigidity of the structure. The drive is taken by a 6 mm diameter leather belt from a stepped pulley on an intermediate shaft of the movement. The original recorder had a bevel gear drive on a silver-steel shaft, but the more elastic belt drive was substituted to reduce the stresses due to the application of essentially intermittent impulses from the escapement to the frame and drum system, the moment of inertia of which is considerable (of the order of 10^5 kg-cm^2).

The frame antenna measures 2 metres square and

0·4 metre deep. It is wound on a spider of paxolin tube, with teak centre and corner bearers, the weight of frame and winding being some 12 kg. The evolution of this light antenna is of some interest; the first frame antenna used in quantitative work at the station, having been wound in copper wire on solid timber, weighed about 75 kg. Later frames were wound in aluminium on hollow aeroplane spar spiders, and paxolin was finally substituted on account of its excellent mechanical and dielectric properties, coupled with the fact that it cost no more than hollow wood spar. The resulting 12 kg antenna has a higher value of area-turns and inductance than had the original 75 kg structure.

The winding of the antenna is in four sections, two of 20 turns each, and two of 10 turns, each of 1·2 mm diameter bare aluminium wire, with a winding pitch of 5 mm. The sections are separately terminalled for series or parallel groupings; normally they are connected in series. The taking up of sag due to initial stretching and to thermal expansion of the wire in varying climatic conditions is of considerable importance in closely wound frames of large size; it should be accomplished without increase of leakage paths such

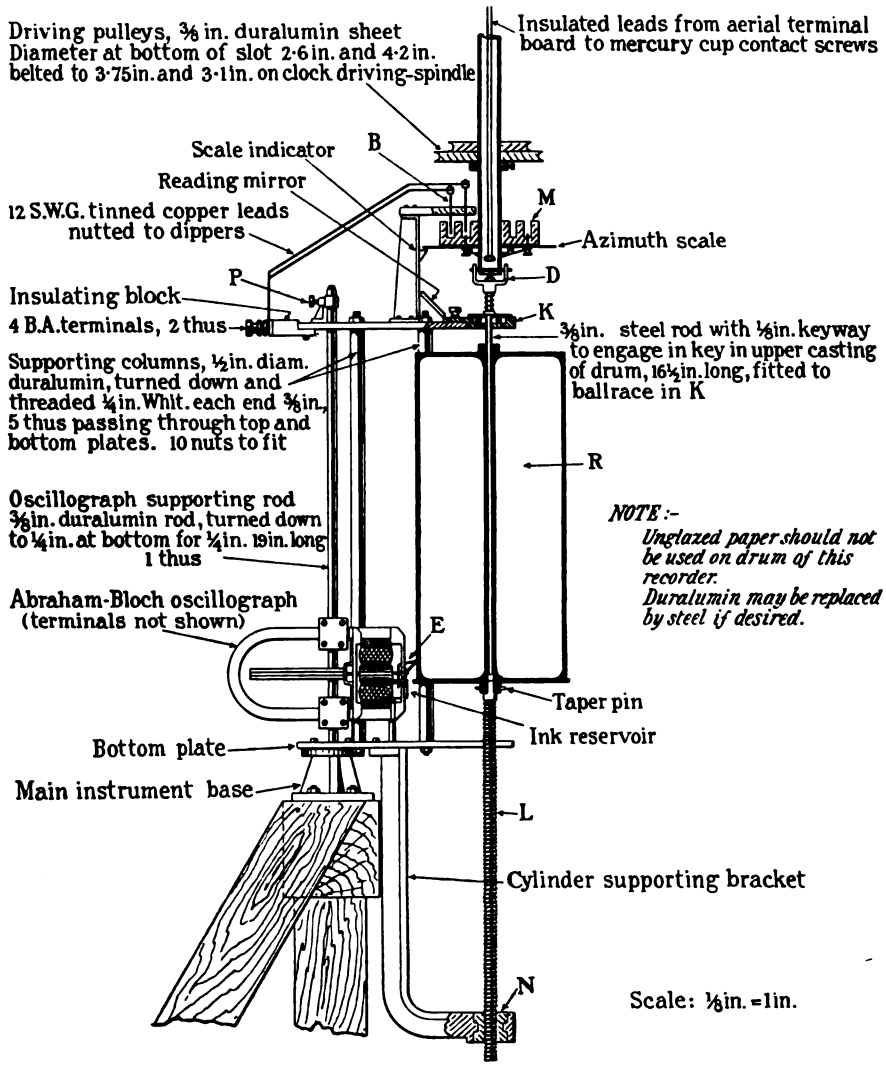

FIG. 2.—Details of recorder.

B = Two 14 S.W.G. copper dippers passing through ⅜ in. paxolin sheet, 3 in. × ¾ in., secured to pillar support with 4 No. 6 B.A. screws.
D = Forked brass casting.
E = Girder pen.
K = Ball-race housing.
L = ⅜ in. steel rod 15 in. long; 1 in. turned down to ¼ in. to fit bottom drum casting; bored for taper pin. Thread ⅛ in. pitch.
M = Mercury cup; 1 in. × 4 in. diam. bakelite-delecto, bored 1 in. in centre with 2 circular channels ½ in. × ⅜ in. deep, fitted steel contact screws. Secured to shaft by collar and pinching screw.
P = Pen-adjusting mechanism.
R = Recording drum, 6 in. outside diam. × 13½ in. long, in brazed copper tube, brass castings at ends bored for centre tube after assembly; centre tube internal diam. to clear ⅜ in. rod. To run true to 1/100 in. in passing pen point.

as was introduced by the first device of combs, in the middle of each span, connected by tension springs to the central boss. The final device, which has proved thoroughly satisfactory, was the introduction of four heavy volute springs in compression in each corner member of the spider. These springs compress 3·5 cm per 100 kg load, and the average compression in each paxolin member of the spider is about 150 kg at normal temperature.

The insulation and pitch of the winding are maintained by winding in locating grooves in paxolin rods carried on each corner member.

The frame antenna hangs freely, by means of a duralumin tube (G) of 2·5 cm diameter forming part of the composite main axis of the antenna frame, from a self-aligning ball race—nominally a radial bearing but employed as a thrust bearing in preference to the standard thrust bearing, which was found to have more friction—carried in the upper member of the main framework. A similar duralumin shaft (H) is carried through a radial bearing in the lower member of the framework 1·25 metres above ground, and carries driving pulleys, tuning condenser, mercury "slip-rings," and an azimuth scale. The shaft terminates in a pin which engages with a fork (D) for transmission of rotation to the recording drum. A variable condenser (J) of maximum capacity 0·01 μF is connected across the winding, and a pair of leads is brought through the lower duralumin shaft from the terminals of this condenser to the mercury slip-rings carried in a moulded insulating collar (M); into these slip-rings dip stout copper brushes connected to the input terminals of the amplifier.

The amplifier is fitted with five stages of resistance-capacity coupling, followed by a detector and two stages of transformer-coupled low-frequency amplification. Provision is made for the use of a varying number of the high-frequency stages, three such stages being normally used for recording atmospherics. The coupling resistances of 100 000 ohms each are wound from 0·04 mm diameter constantan, on slotted ebonite formers, the direction of winding being reversed in alternate slots to reduce the total inductance. The ordinary anti-inductive winding is objectionable on the grounds of self-capacity, whilst the special anti-inductive and anti-capacitative windings are too bulky and too costly to be justified in this application. The adoption of wire-wound resistances was found necessary on account of the very high temperature coefficients of resistance of the more usual forms of anode resistance. The residual temperature coefficient of constantan is actually slightly advantageous, since its sign is such as to assist in compensating the temperature coefficient of voltage of the plate circuit accumulator battery. Carbonized cellulose grid-leaks, although objectionable, were retained in the standard design, *faute de mieux*. A milliammeter is provided in the common plate circuit lead to the first seven stages, measuring the sum of the plate currents in these stages, whilst a second milliammeter measures the current in the output stage. A switch and series resistance are provided so that the former milliammeter can also be used as a voltmeter for the plate circuit battery. The coupling elements are well spaced to reduce stray couplings, and negative capacitative retroaction is provided for stabilization. The amplifier is contained in a teak case 50 × 28 × 28 cm, with ebonite front and top, the front carrying meters and controls, the top carrying triode sockets.

The triodes used are dull-emitters with 1·8 volt, 0·3 ampere filaments. All except the last stage are of the D.E.R. type with internal impedance of the order of 30 000 ohms, whilst the output stage contains a D.E.6 triode of 13 000 ohms impedance. Accumulators (90 ampere-hour), crated in groups of three, are used for filament lighting. They are charged in series and discharged in parallel, and no important fall in voltage takes place in 24 hours; thus with a slight adjustment each day a sensibly uniform current is maintained throughout four days at one charge. The plate batteries are 60-volt units of 1·25 ampere-hour capacity, with ribbed glass cases, so arranged that each individual cell is visible for maintenance. Similar cells are used in a 10-volt unit which maintains the normal grid potential of the output triode at − 10 volts. This gives rectification of the output current, eliminates interference by transmitting stations, and selects only the stronger atmospherics for recording.

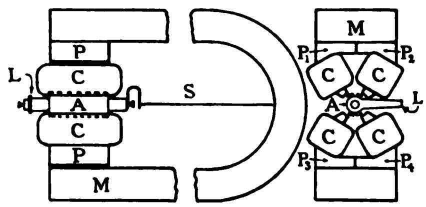

FIG. 3.—Abraham-Bloch oscillograph.

The oscillograph (Fig. 3) inserted in the plate circuit of the output triode is a tetrapolar moving-iron instrument, designed by Abraham and Bloch,* and made by the Carpentier workshops in Paris. It comprises a permanent magnet M with four laminated radial poles P_1 to P_4, each carrying a coil C, the coils being so connected that the passage of a current rotates the resultant magnetic field to a new direction. The solid soft-iron armature (A) in following this rotational displacement produces torsion of the steel-wire control spring (S). The coils have a total resistance of 10 000 ohms, the armature has a moment of inertia of 2·75 g-cm^2, whilst the restoring couple per unit displacement is of the order of 10^6 dyne-cm. The free period of the armature is about 0·01 sec., strong magnetic damping being obtained by the non-lamination of the armature.

A tongue on the armature shaft carries a pen girder (Fig. 4) in aluminium. The girder, cut from sheet 0·2 mm thick, is 9·5 cm long, and carries a siphon pen of silver tube of bore 0·12 mm and total length 3·5 cm. The total weight of girder and pen is 0·4 g. This pen dips into an inkwell of adjustable height; the pen will feed from a negative head of over 1 cm, but it is usually operated at a head between zero and 2 mm. The girder is designed to give considerable rigidity in its own plane, combined with flexibility in a plane at right angles, so that pen friction may not be

* *Revue Générale de l'Electricité*, 1920, vol. 7, p. 211.

unduly increased by slight irregularities in paper thickness, truth of drum, and such causes. Residual variations in pen friction are not important in view of the large working forces of the oscillograph.

The recording drum (R in Fig. 2) is a vertical brass or aluminium cylinder 34 cm long by 15·3 cm diameter, with a square-threaded steel lead-screw (L) of 3 mm pitch pinned to its lower end. This lead-screw works in a nut (N) clamped in the recorder stand.

No direct quantitative calibration of the response to atmospherics can, for the reasons given in Section IV (3) following, be made. For the purpose of determining a typical overall performance, however, recourse was had to measurement with a steady input at 15 kilocycles, with 100 per cent modulation at 1 kilocycle, and the results are shown in Fig. 5.

The oscillograph pen gives a deflection of 3 mm per milliampere for small deflections.

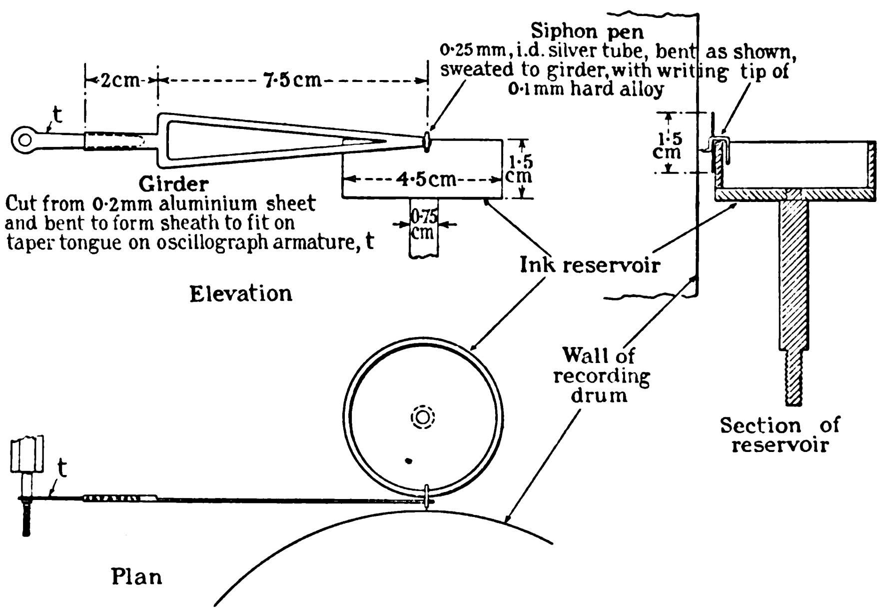

Fig. 4.—Girder siphon pen.

The fork (D) already mentioned turns, in a radial non-self-aligning bearing, a guide rod in which is cut a longitudinal (vertical) keyway; a feather on the bore of the drum engages in this keyway, carrying over the rotation of the frame antenna to the drum, which is simultaneously lowered by the lead-screw. The chart is a rectangle 49 cm × 34 cm wrapped around the drum, resting on the lower flange, and with a vertical 1 cm lap joint secured by photo mountant. The housing of the small radial bearing, and the lead-nut, are secured by clamping devices so that the system comprising guide rod and bearing, drum, lead-screw and nut can be lifted out as one unit for chart-changing and re-setting of the nut to the lower end of the lead-screw. On removal from the drum the helical trace is resolved into 96 approximately horizontal lines, each representing one revolution, or 360° in angle, and 15 minutes in time at the normal speed of rotation.

Electrical constants.—The frame antenna has a maximum inductance of 13·5 mH and is tuned to 15 000 cycles (20 000 m) by the variable condenser. The d.c. resistance of the four sections in series is 10·8 ohms, whilst the high-frequency resistance at the working frequency is 50 ohms. This comparatively high value might of course be reduced by sacrificing the wide band of wave-lengths for which the instrument is designed.

Operation.—It will be seen from the description that the method of operation of the recorder is as follows. The turret clock drives the frame continuously at a speed of 4 (or if desired 8) revolutions per hour. The fork connector and guide rod transmit this rotation to

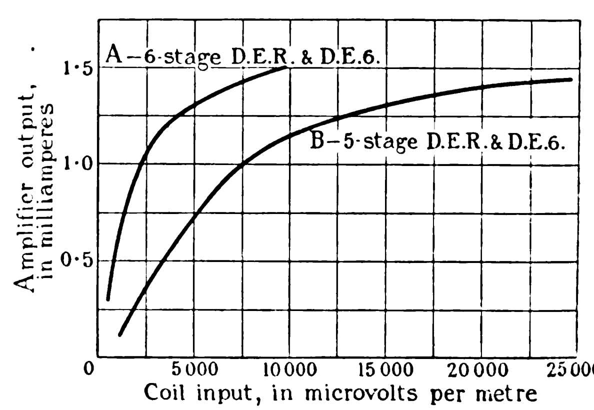

Fig. 5.—Calibration of recorder.

the drum carrying the chart, and the lead-screw feeds down through its stationary nut, so that the drum descends through 3 mm per revolution. The oscillograph pen will thus, in the absence of impulses from

the amplifier, describe a helical trace of 3 mm pitch on the chart. The arrival of an atmospheric producing a sufficient voltage release in the amplifier will be marked by a vertical excursion transverse to the helical base. The amplitude of this excursion will, within limits to be mentioned later, be a measure of the voltage produced across the tuning condenser, and its position on the trace will be a direct measure of (*a*) the time of arrival of the atmospheric and (*b*) the instantaneous azimuth of the plane of the frame antenna at that moment; since the drum is directly coupled to the frame, all impulses received when the frame is in a given azimuth will appear on the same generator of the cylinder formed by the chart.

If then we had a single sharply-directed stream of uniform atmospherics impinging on the antenna, a single revolution would give a trace in which the lengths of the transverse kicks due to atmospherics departed from a simple function of the cosine of the instantaneous angle between the plane of the frame and the axis of the " beam " of atmospherics, only on account of the non-linear response of the amplifier and the oscillograph. The envelope of the extremities of the deflections would, in any case, be a double-humped curve with two sharply-marked minima locating the plane perpendicular to the axis of the beam.

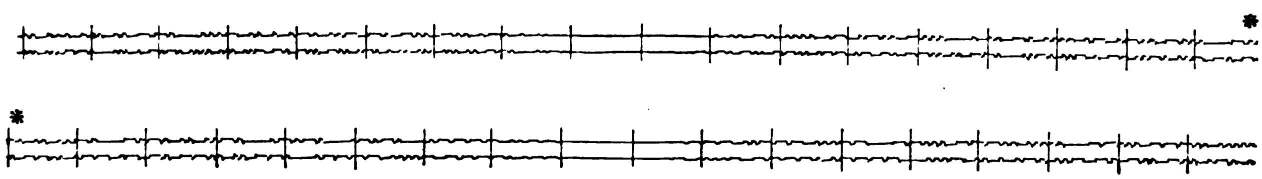

FIG. 6.—Signal trace from recorder.

The very wide range of variation in peak field strength, rate of change of field strength, duration and relative times of arrival of atmospherics, and of the position of their sources, precludes the possibility of obtaining an actual record corresponding to this ideal case, but the nature of the response is well shown in Fig. 6, which is a record of the deflections, over two whole revolutions, due to a received signal from Ongar (GLO) wireless telegraph station.

IV. DEFECTS AND LIMITATIONS.

The recorder is obviously a somewhat crude device, far short of the ideally quantitative, sharply directional and discriminating recorder which is desirable. But it was considered worth while to develop and run an instrument which has the very real merit of demanding practically no maintenance attention other than chart changing and accumulator charging, so that it might be providing preliminary data while more fundamental work, the progress of which was certain to be slow, was being carried out along with other lines of investigation on atmospherics.

The principal defects of the method are as follow :—

(1) The instrument is non-discriminating, in that it deals with the average direction of arrival of the whole distribution of atmospherics. The large area enclosed by the polar curve of reception, the cosine curve of the ordinary frame aerial, involves the superposition of effects from all azimuths, so that, for example, the appearance of a small disturbance at a position on the chart corresponding to azimuth ψ may correspond to the arrival of an atmospheric of small amplitude along the great circle of azimuth ψ or $\psi + 180°$, or of a moderate atmospheric from $\psi + 40°$, or of a strong atmospheric from $\psi + 80°$. Thus it is to be expected that at times the trace will be too much complicated by dispersed directions of arrival to give an intelligible record of the distribution; but, as will be seen later, these cases are comparatively rare, and a single predominant stream of atmospherics is generally traceable from the records.

(2) The instrument is only quantitative within somewhat narrow limits, the lower limit being set by the comparative insensitivity imposed by the use of a pen-writing oscillograph. This limit would, however, have appeared in any type of incompletely discriminating recorder, since the traces from an oversensitive instrument cannot be interpreted. The upper limit, imposed by saturation of the triodes in the final stages, and by the characteristic curve of the oscillograph, is a more objectionable factor, but again narrow limits must be imposed on any type of recorder if a 24-hour record is to be compressed in a reasonable area of paper. Were the limitation of deflections to the order of a few millimetres not imposed by the amplifier-oscillograph system, it would be necessary to impose it otherwise, unless a tape record of inordinate length were to be tolerated.

(3) The instrument gives a deflection the amplitude of which, for any one atmospheric, depends not simply on the peak field strength or on a simple function of that field strength, but on the wave-form and duration of the impulse, in relation to the characteristics of the tuned circuit and of the moving-iron oscillograph.

(4) The record becomes too sparse to be interpreted if the total amount of disturbance falls to a low value. This reduces the applicability of the instrument for the study of what might otherwise be the simplest distributions experienced.

(5) The sense of the direction of arrival is not determined, i.e. the normal radiogoniometric ambiguity of 180° remains.

V. ADVANTAGES.

These defects and limitations, formidable as they may be, are, after all, common in greater or less degree to all normal direction-finders, and the data supplied, though far short of the absolute standard, may on this account be expected to be comparable with that from aural directional observations. But whilst it is practically impossible to devote sufficient labour to aural recording to provide more than five test observations

daily, and whilst these observations are subject to errors of sampling and to large personal factors, the recorder gives fair sampling under relatively invariant observational conditions throughout the 24 hours, the total time devoted to maintenance and to reduction of records being less than would be required for the inadequate aural sampling. In particular, the instrument is ready at all times to record special phenomena, whilst the aural observer is, by the exigencies of everyday life, practically limited to fixed-hour observations if any protracted period is to be covered, and is seldom beside his apparatus when conditions of special interest arise suddenly.

The recorder has the further advantage that its trace is available for re-examination in case of doubt, or when a new line of investigation suggests itself.

Finally, the recorder enables data to be collected at widely scattered stations without the provision of specially trained and skilled observers.

A click recorder.—It is, however, to be kept clearly in mind that, partly by the inherent characteristics of its components and partly by deliberate choice and adjustment, the recorder is almost exclusively a "click" recorder, giving traces in which the strong, comparatively isolated, impulses, comparable in aural effect with those received in daylight from lightning within 1 000–2 000 km, predominate over the more continuous stream of relatively weak disturbances which may, on account of its continuity, be a more serious interferent agent in long-distance radio telegraphy. Thus it will be necessary, in comparing results with those of other methods, to remember that every method is selective as to the type of disturbance receiving most weight in the measurement, and the differences resulting from this selectivity, though confusing at first, may be expected to throw light on the origins of different elements in the general distribution of atmospherics.

Maintenance and reliability.—The average amount of time required for maintenance, accumulator changing and chart changing is somewhat under $\frac{1}{4}$ hour per day. The reliability of running may be inferred from the results of the first $2\frac{1}{2}$ years' experience, with the first instrument of its kind, at Aldershot. The total number of "lost hours," i.e. hours when no record, or a record marred by remediable instrumental faults, was obtained, averaged 8 per cent over the whole period, but fell to 3 per cent over the last $1\frac{1}{2}$ years. The higher percentage losses in the first year were due in part to lack of mechanical rigidity affecting the clock drive, and in part to considerable difficulties with early dull-emitter valves, now happily surmounted by the extreme reliability and constancy of the D.E.R. valve. It need hardly be pointed out that it was the advent of the dull-emitter which made the instrument practicable for general issue, since a recorder using 6 to 8 bright-emitters for 24 hours each day involves accumulator charging on an almost prohibitive scale.

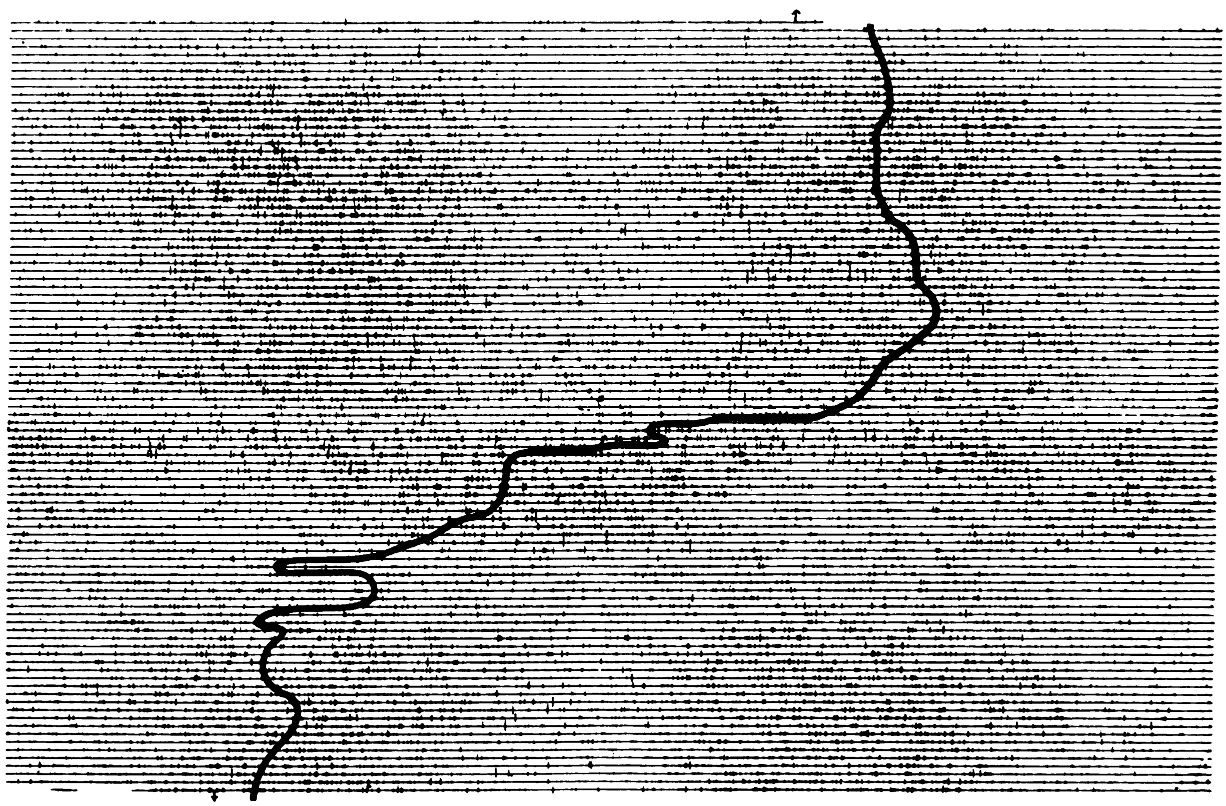

FIG. 7.—Typical daily chart.

VI. Reduction of Records.

The reduction of the resulting records may be carried to varying stages of completeness, according to the use to which the data are to be put. Mere visual inspection of the chart in situ is usually sufficient for a determination within 10 degrees of the apparent direction of arrival and for estimation of the relative intensity of disturbance. It is believed that a much smaller instrument could now be designed for used in an ordinary room, and that a number of such instruments would help to clear up many of the remaining obscurities in the problem of atmospherics.

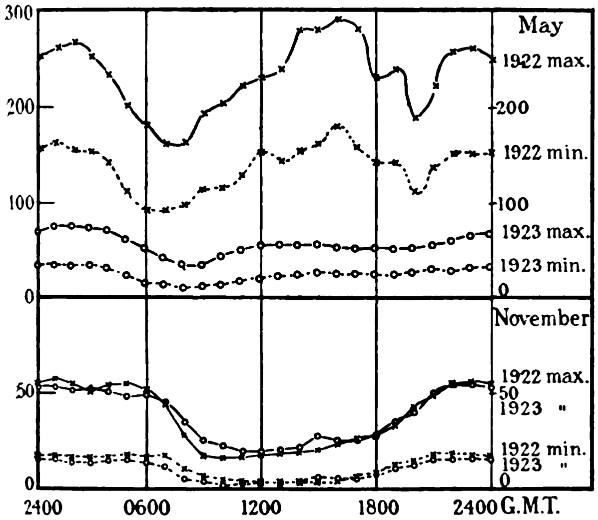

Fig. 8.—Diurnal variation of intensity.

For closer and more complete study of the direction of arrival, the charts are examined line by line, and the most probable direction of maximum disturbance is determined by location of the two maxima 180° apart and two minima approximately midway between these maxima. The points so found are joined by a more or less continuous line traversing the chart, from which can be read the mean azimuthal position of the frame antenna against which appear the greatest number of recorded atmospherics of large or moderate amplitude in each hour. This is accepted as the mean apparent direction of arrival of atmospherics for the hour. Fig. 7 is a typical chart, with the line of most disturbed azimuths drawn in. It is frequently possible to trace double distributions, and in many cases a "grinder maximum" marked by the occurrence of large numbers of disturbances of small amplitude can be located with some accuracy, in addition to the location of the "click-maximum."

The accuracy with which these azimuths can be determined is, of course, difficult to specify. There is no doubt that, regarding the mere reduction of the trace, discrimination to about 2° in azimuth is normal. How far this is from corresponding to a 2° accuracy in discriminating the great circle joining the source of atmospherics to the recording station can only be inferred from comparison of the resulting data with data otherwise obtained.

This directional reduction is a relatively simple and brief process. If, however, estimates of relative intensity are required a somewhat laborious process is involved. The charts are ruled with a graticule dividing them into blocks of which the width represents 10° in azimuth and depth 1 hour in time. The integrated departure from the base line in the blocks containing the maximum and minimum disturbance are then determined by an opisometer, and the "intensity at maximum" and "intensity at minimum" for each hour are tabulated, on the arbitrary scale resulting from the complex process of reception, amplification, rectification, magnification, limitation, re-rectification, recording and measurement.

It cannot be pretended that the sensitivity of the whole instrument can be kept nearly constant from day to day, but it is most probable that the relative disturbance from hour to hour of the same day, and the mean intensities measured over long periods, will be comparable. The first typical data to be presented will illustrate this point.

Table 1.

Interval (in hours) between times of the various stationary points and the times of the solar phenomena to which they are related.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
M_1 after sunset	6	6	$5\frac{1}{2}$	$5\frac{1}{2}$	6	$6\frac{1}{2}$	$6\frac{3}{4}$	$7\frac{1}{2}$	7	7	$6\frac{1}{2}$	$6\frac{1}{2}$
M_2 before sunset	4	$4\frac{1}{4}$	5	5	4	5	6	$5\frac{1}{2}$	5	4	—	$4\frac{3}{4}$
M_3 before sunrise	2	2	$2\frac{1}{4}$	3	$2\frac{1}{2}$	$2\frac{3}{4}$	$2\frac{3}{4}$	$1\frac{3}{4}$	1	$1\frac{1}{4}$	—	1
M_4 before sunset	$\frac{1}{4}$	$2\frac{1}{4}$	1	—	1	$\frac{1}{4}$	1	$\frac{3}{4}$	$2\frac{1}{2}$	$2\frac{1}{4}$	1	$\frac{3}{4}$
N_1 after sunrise	$3\frac{1}{4}$	$2\frac{1}{2}$	$3\frac{1}{2}$	—	$3\frac{1}{2}$	—	5	$5\frac{1}{4}$	5	$4\frac{3}{4}$	4	—
N_2 after sunset	$\frac{1}{4}$	$-\frac{1}{2}$	0	0	$\frac{1}{4}$	—	$\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	0	$-\frac{1}{2}$

Note :—M_1 and M_3 coalesce in August.
M_3 nearest sunrise save in June and July, when M_1 crosses.

VII. The Diurnal Variation in Intensity of Disturbance.

Data as to the monthly mean value of the intensity of disturbance at each hour of the day, for the hourly azimuths of greatest and least disturbance, are available from the Aldershot records from January 1922 to August 1924. The curves for the months of May and November are shown in Fig. 8 as illustrating the greatest and least diversity in intensity experienced for the same months in different years; they serve particularly to emphasize the close agreement between the trends plotted in Fig. 9. It will be noted that each monthly curve contains some 7 or 8 stationary points, and that of these there stand out prominently a principal maximum M_1 in the hours of darkness, a secondary maximum in the early afternoon, a principal minimum N_1 before noon, a secondary minimum in the early evening, and subsidiary maxima in the early morning and evening. The times of incidence of these stationary points are plotted in Fig. 10, in which are also shown the mean times of sunrise and sunset for each month. It is immediately obvious that a close correlation exists between the incidence of the

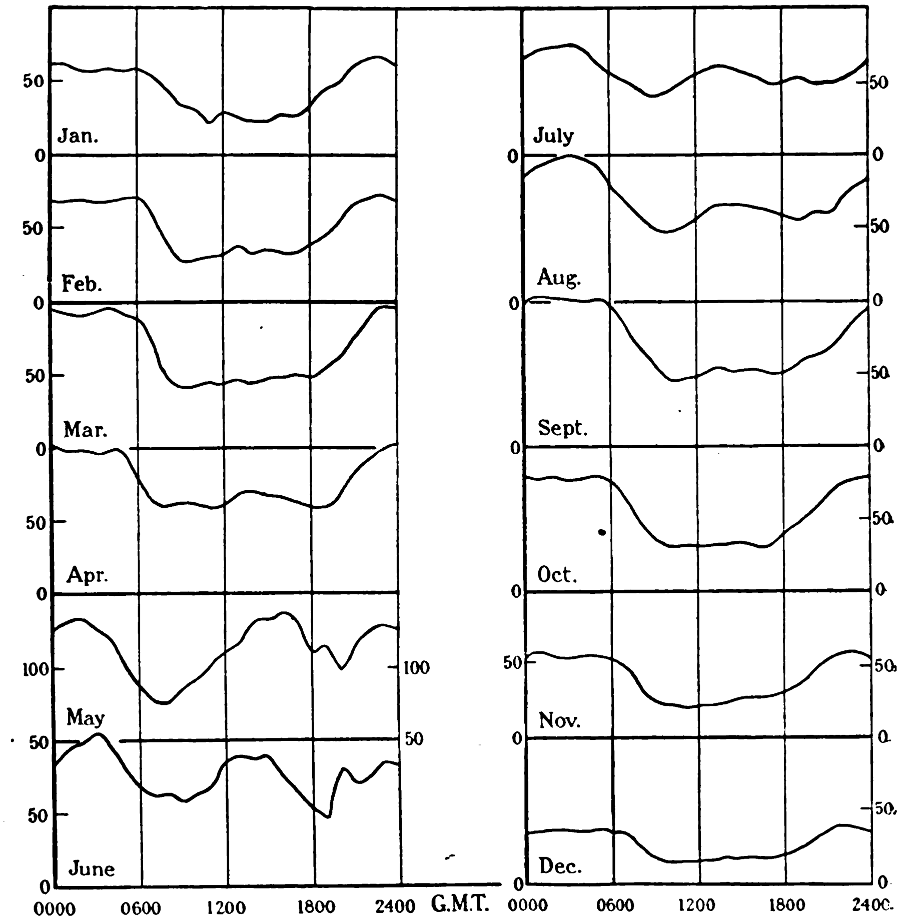

Fig. 9.—Diurnal variation of intensity.

of the intensity curves at the directions of maximum and minimum disturbance, and the constancy of form of the diurnal variation, even in years where the actual amplitudes differ considerably. The similarity of the curves of intensities at the directions of maximum and minimum disturbance is doubtless very largely due to the wide polar curve of the frame antenna and need not at the moment be examined further, since more refined methods will improve our discrimination in this respect. The form of the diurnal variation will therefore be discussed with reference to the values from the direction of maximum disturbance throughout. The mean monthly curves for the $2\frac{1}{2}$ years' data are maxima and minima of disturbance and the times of zero solar altitude at the receiving station. Table 1 shows the approximate constancy of the intervals between the times of the various stationary points and the times of the solar phenomena to which they are related. It may be added that similar relations hold for some of the still less prominent irregularities which appear in the curves of Fig. 10.

Speaking generally, then, the diurnal variation of atmospheric disturbance in a long-wave receiver in England may now be described, with much greater accuracy and confidence than has formerly been possible, as reaching a maximum 6 hours after sunset,

the fall from the maximum being temporarily interrupted by a slight increase 2½ hours before sunrise. (In May and August the maxima coalesce, whilst in June and July they are reversed in sequence, owing to the shortness of the sunset to sunrise period.) The minimum disturbance of the day is reached some 4 hours after sunrise. An increase, most marked in summer, then begins, and reaches a maximum 5 hours before sunset (this maximum is just detectable in winter, and in summer rises to the same order of amplitude as does the principal maximum). The fall to a secondary minimum at sunset is interrupted by a slight increase 1 hour before sunset.

arrival in the same general statistical fashion as has been used in the case of intensity values. The main difficulty, to which reference has already been made on page 599, is that due to the ambiguity of 180° in the determination of azimuth. This ambiguity renders difficult the selection of a direction which may be accepted as characteristic of a period. If, for example, a "mean direction of arrival" for a period is to be extracted, the mean will be widely displaced by the reversal of the sign attached to directions approximately 90° from the mean. In the former papers cited, the mean was extracted on the specific assumption that the distribution was approximately symmetrical about

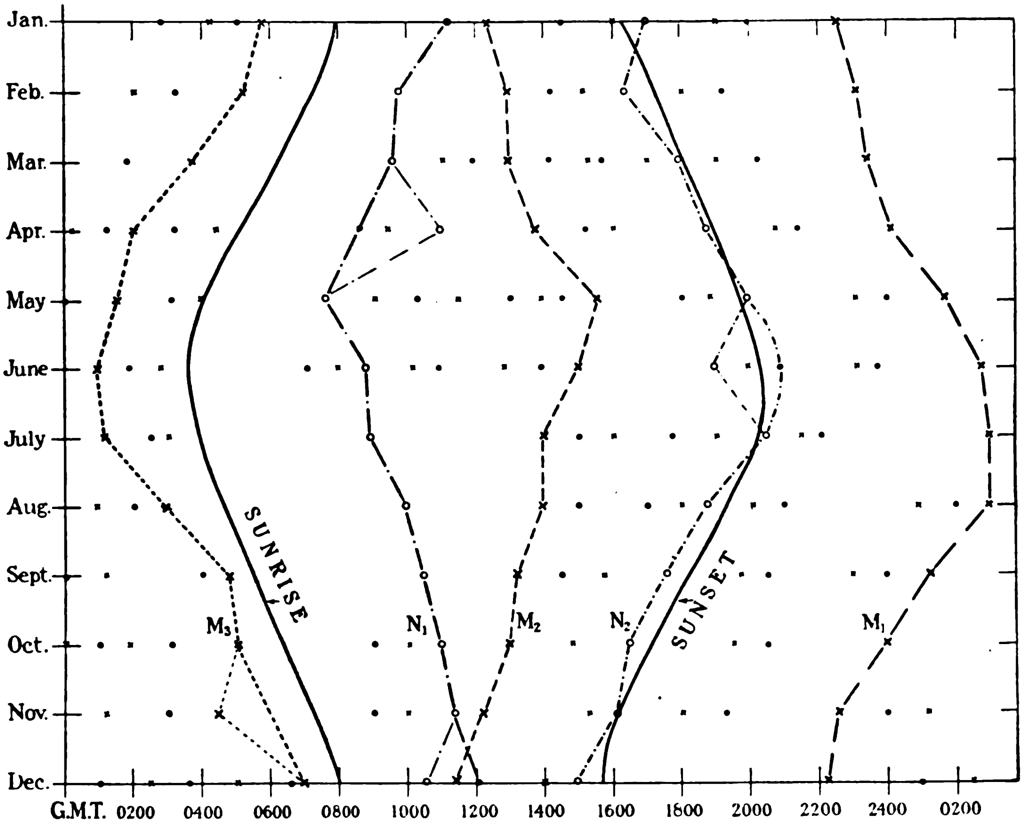

Fig. 10.—Principal stationary points in intensity curves.

Since these relations were examined, a paper * has appeared dealing with diurnal variation curves based on observations through one sample day per week in the years 1923–24. In view of the interest attaching to a comparison of these results, and of the fact that the present paper is intended rather as indicating the scope of the recording methods described than as a discussion of resulting data, it appears desirable to leave such discussion for another occasion.

VII. Diurnal Variation of Apparent Direction of Arrival.

Certain difficulties present themselves when an attempt is made to treat the apparent directions of

* L. Espenschied, C. N. Anderson and A. Bailey: "Transatlantic Radio Telephone Transmission," *Electrical Communication*, 1925, vol. 4, p. 7.

the mode or most frequent value. A careful survey of records from the apparatus described in this paper, however, shows that multiple distributions, with two independent directions of strong disturbance showing simultaneously, are sufficiently numerous to prevent the mean so determined from having a real objective significance. It was finally decided that the principal features of the records were most clearly expressed by the process described in the next paragraph.

The daily records were reduced by the allocation of the apparent direction of arrival for each revolution of the frame, i.e. for each ½ hour of the day, and a curve, continuous except for breaks resulting from inability to determine a most disturbed azimuth, was drawn through the points thus located. From this curve were read off the hourly values of apparent direction of

arrival, for hour periods, centred on hours G.M.T. These hourly values were then entered in a distribution diagram covering a whole month, which thus showed the number of occasions in the month on which, at any selected hour, a selected azimuth had been most disturbed. The whole of the 360° of azimuth, in 5-degree steps, was plotted, and entries were made corresponding to both possible senses of the ambiguous determination. These distribution diagrams thus showed the general trend of the diurnal variation during the month; there were homogeneous blocks of frequent disturbance seems to be a more sensitive index of variation than is the mode (i.e. the most frequent value), and less liable to mask objective realities than is the mean. A sample distribution diagram is shown in Fig. 11. This diagram for the Ditton Park records of October 1924 is somewhat simpler than the average, but serves to illustrate the method of extracting hourly median values, and shows very clearly the type of diurnal variation about to be discussed.

It will be seen from Fig. 11, in which the median of the principal disturbance block for each hour is under-

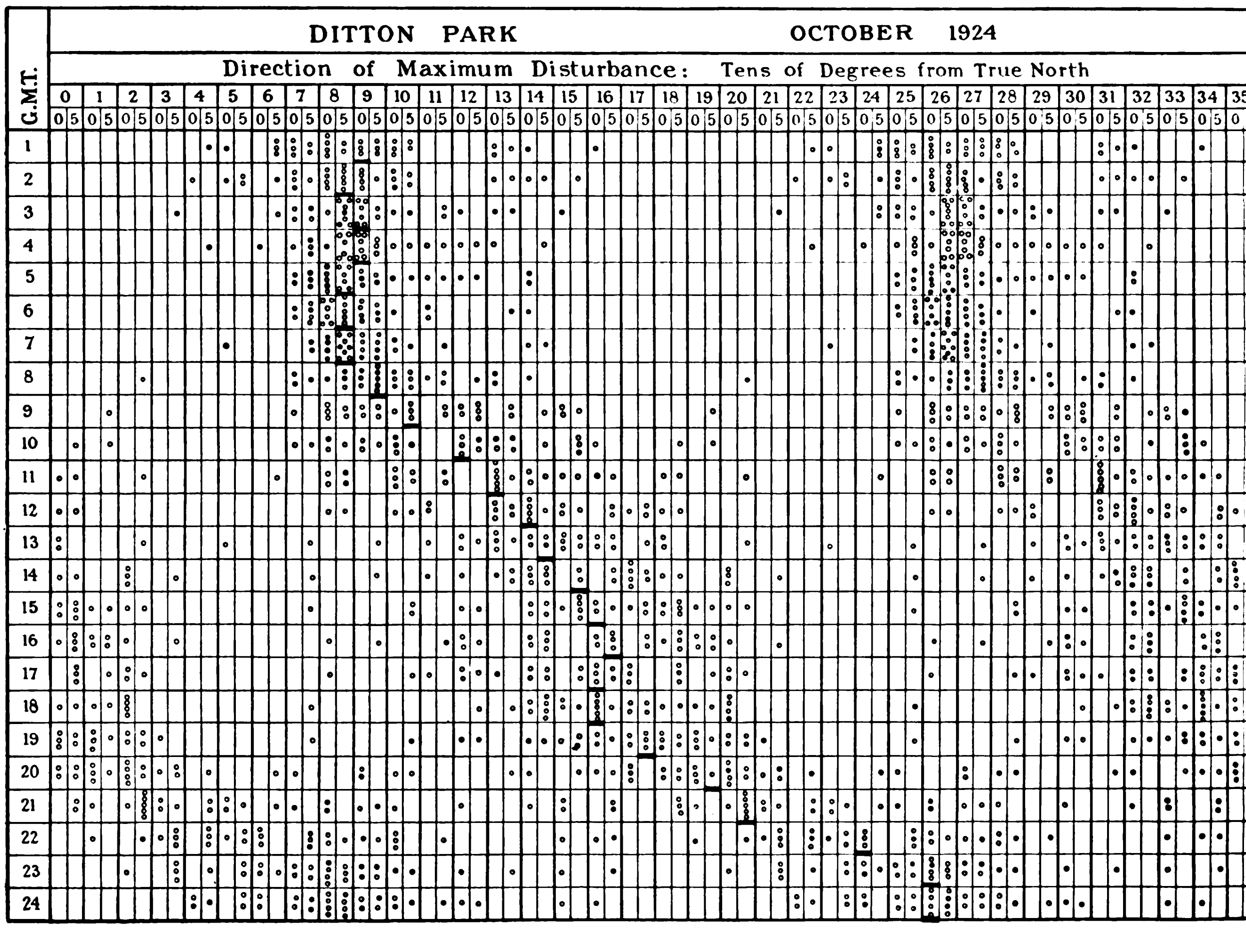

FIG. 11.—Frequency chart of hourly variation of direction of maximum disturbance.

separated by blocks showing no entries whatever for the whole of the month. Some elasticity of judgment was allowed in the separation of the blocks; in general a gap of 20° in azimuth was accepted as significant of a real difference of origin, i.e. as separating two different streams. The "medians" of these blocks, i.e. the azimuths which had as many observations (within the block) on one side as on the other, were then selected as specifying the most probable value of the predominant hourly directions of arrival for the month. If the method of separation of blocks of disturbances be accepted, no great difference occurs amongst mean, modal, or median values for the block, but the median lined, that the direction of greatest disturbance appears to swing through 180° in 24 hours. Actually it must, of course, swing through 360°; since 2400 h immediately precedes 0100 h, and, since the rate of swing is slight in the hours of darkness, there must be approximate identity between the median values of these two hours, and not the 180° difference which would, superficially, appear.

To enter into the full discussion of this most interesting aspect of the records would again be to overload a paper descriptive of an instrument and its applications, and it must be confessed that there are notable obscurities which the author could not yet undertake to remove

even in an *ad hoc* paper. He must, therefore, restrict himself to the presentation of Table 2, showing the predominant apparent directions of arrival of atmospherics at Lerwick, for the period October 1924 to March 1925. This table is offered as a second sample of the type of data which may be obtained systematically, under controlled and specified conditions and limitations, by the directional recorder forming the subject of the paper.

The resolution of the ambiguity.—Experiments were made at various times, in the course of the investigation, on the resolution of the radiogoniometric ambiguity of 180°. The first series of such experiments, in 1916, resulted in the introduction of an unambiguous direction-finder for aural work.* With this instrument it was determined that the direction of arrival during the daytime was certainly from the south-east quadrant rather than from the north-west. Economic considerations, however, enforced the adoption of the rotating frame aerial in place of fixed loops, and no extensive observations were then made with the device. It was not until 1922 that experiments in this direction were resumed, this time with a view to making the directional recorder unambiguous. The difficulties in the way of this conversion that were in the earlier work, and that are still, so far as the author's information goes, experienced by all who deal with the now fairly familiar heart-shaped diagram, were that the sharpness of minimum attainable in unambiguous direction-finders is, on the average of protracted periods, very much inferior to that attained in the ambiguous polar curve, and that the constancy of adjustment required for continuous recording on an unattended instrument is difficult of attainment. For these reasons the determination of sense has usually in ordinary radiotelegraphic practice been made a subsidiary operation with comparatively blunt minima, but an atmospheric recorder based on a similar surrender to difficulties would have been a clumsy and inelegant compromise.

* British Patent No. 129336.

The obstacles were sufficiently satisfactorily surmounted to enable simultaneous records to be taken on an ambiguous and on an unambiguous recorder in May and June 1923.

This degree of success had scarcely been attained, however, when it became necessary to erect new aerials of large capacity for work on the wave-form of atmospherics, the field round the unambiguous recorder was so distorted by the new aerials that the polar diagram returned to a figure of eight, the station staff were devoting their whole efforts to the wave-form work, and the unambiguous recording was relegated to a day, not yet reached, when pressure of more fundamental investigations should permit of its resumption.

The brief trial period did, however, provide the clue to the problem of diurnal variation. As reported in the discussion of a valuable paper by the Marconi Research Staff,* the normal type of diurnal swing in a test period in May was of the nature of that shown in Table 2, but with the important addition that the time of a somewhat sudden change of 180° in the direction of arrival was located.

Instead of attempting any complete analysis of the diurnal variation, which must on account of incomplete data and limitation of space be unsatisfactory, it appears desirable to limit the discussion to one selected sample. The relatively high latitude of Lerwick results in its showing a much simpler distribution of atmospherics than do the stations in middle latitudes, although there is some evidence from the Bangalore record that low latitudes also have relatively simple distributions. Aboukir's monthly distribution diagrams almost invariably show double maxima, and Ditton Park shows similar complexity for a great part of the year. Lerwick is, therefore, a very suitable station for an elementary study of diurnal and seasonal swings.

It will be seen from Table 2 that an apparently

* J. H. Round, T. L. Eckersley, K. Tremellen and F. C. Lunnon *Journal I.E.E.*, 1925, vol. 63, p. 933.

TABLE 2.

Lerwick Recorder. Apparent Direction of Arrival of Atmospherics.

Hours (G.M.T.)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
September .	253	254	256	258	259	263	264	268	271	275	115	117	127	143	150	153	123	135	166	170	179	210	225	248
October ..	258	263	262	262	259	256	256	262	267	97	114	134	138	144	149	146	149	147	162	175	194	228	238	254
November .	243	243	242	242	242	242	243	253	257	110	134	140	142	147	150	157	153	164	177	214	229	237	245	242
December .	228	229	227	224	218	224	231	238	248	155 242	185	180	195	189	198	194	180	185	204	220	228	232	234	234
January ..	229	224	223	222	222	222	226	238	249	182	182	182	187	188	193	210	214	222	227	229	230	—	230	232
February .	233	234	229	229	230	230	232	242	258	190 253	175 250	178 248	175	170	175	190	200	200	218	222	228	230	232	233
March ..	233	228	228	234	235	236	243	252	260	167	170	170	170	170	170	—	—	150	175	205	228	234	283	240

arbitrary change in the adopted sense of the ambiguous directional determination occurs at about 10 hours G.M.T. There is a double justification for this; first the time of the change is approximately that of the change determined by the unambiguous determinations already mentioned; and second, the correlation with solar azimuth makes the seasonal variation readily explicable if this sense is adopted. Thus for the late evening and early hours of the morning the adoption of a westerly sense for the directions fits with a predominant source of atmospherics moving southward with the sun until the winter solstice, and then turning to follow the sun in its northward travel. Were the same sense applicable to the mid-day values the source would be moving northward during that part of the year in which the sun is moving southward.

Thus the general picture which one obtains of the course of the variations in the principal stream of atmospherics is as follows. Early in the morning—sometimes, in fact, before midnight—atmospherics arriving from the far east, where the sun has already attained some considerable altitude, begin to show themselves. Towards 9 or 10 a.m. G.M.T. they have become the dominant stream, and arrive from a direction a few degrees south of east at the time of the autumnal equinox, and from nearly due south at the time of the winter solstice. In the equinoctial season the cum-solar swing of the hourly directions of arrival is very strongly marked, and in all cases the direction of arrival swings through south to a relatively constant SW by W or WSW near midnight.* This stream from the west usually remains the dominant stream until about 9 a.m., presumably because the American Continent produces atmospherics until late in its evening, whilst the Pacific is not an important atmospheric-producing centre. Not infrequently the stream from about 250° E of N can be traced until midday.

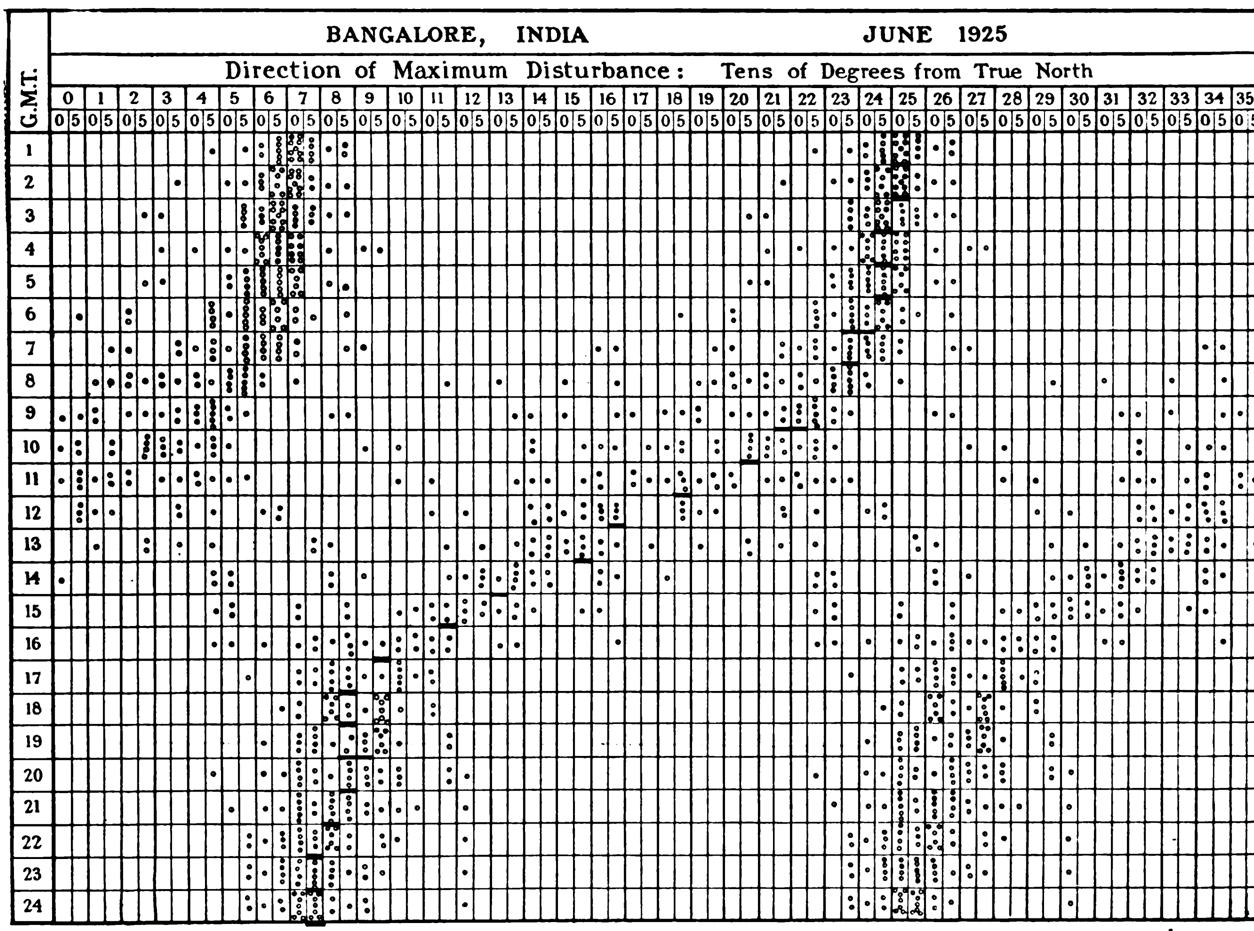

FIG. 12.—Frequency chart of hourly variation of direction of maximum disturbance.

The intensity curves show these two streams, the stream from the west giving, with the help of the improved long-wave propagation in the dark hours, the heavy night disturbance, whilst the secondary day maximum is to be ascribed to the more strongly attenuated stream from the less distant sources in the east and south. The principal minimum marks the combined influence of impaired propagation in daylight, of the diminished activity of the Western source, and of the incomplete development of the stream from the east.

* A cum-solar swing of small amplitude was observed by Schindelhauer (*Jahrbuch der drahtlosen Telegraphie und Telephonie*, October, 1923) in a single month's observations in March 1922.

The simplicity of the equinoctial distribution diagrams from south-east England, as illustrated by Fig. 11, appears to be due to the exact opposition of 180° in the directions of arrival of the decaying westerly and the increasing easterly stream.

It is significant, in relation to this solar control, that the distribution curves for Bangalore in the month of June, when the sun is north of the station, show a clearly marked reversal of the normally clockwise diurnal swing, the resulting counter-clockwise swing being still cum-solar. The diagram is reproduced in Fig. 12.

It was formerly the custom to excuse the use of ambiguous direction-finders by remarking that bearings from a number of ambiguous instruments would give unambiguous intersections. This is true for relatively short-distance work, but it is not true when the source of the observed radiation is at such a distance that the convergence of the bearings is not notably greater than the possible errors of observation, and if we admit the possibility of reception over distances comparable with the earth's semicircumference no network of ambiguous recorders will distinguish between a true source and its antipodes, and even an unambiguous recorder need not point the shortest geographical path to the source, as a long dark path may be easier (radio-telegraphically) than a shorter illuminated path. Thus investigation of the remaining obscurities in the distribution of atmospherics would be far more satisfactorily carried out by a number of instruments of deliberately limited range than by a few long-range instruments.

IX. Sources of Atmospherics.

Sufficient data have not yet been accumulated to show whether stations so far apart as Lerwick and Bangalore generally receive their atmospherics from the same source. Discussion of simultaneous bearings from all stations might, therefore, lead to misleading conclusions from inadequate data. As a last group of samples of recorded data, therefore, it is proposed to cite only two series of intersections from the group of recorders comprising :—

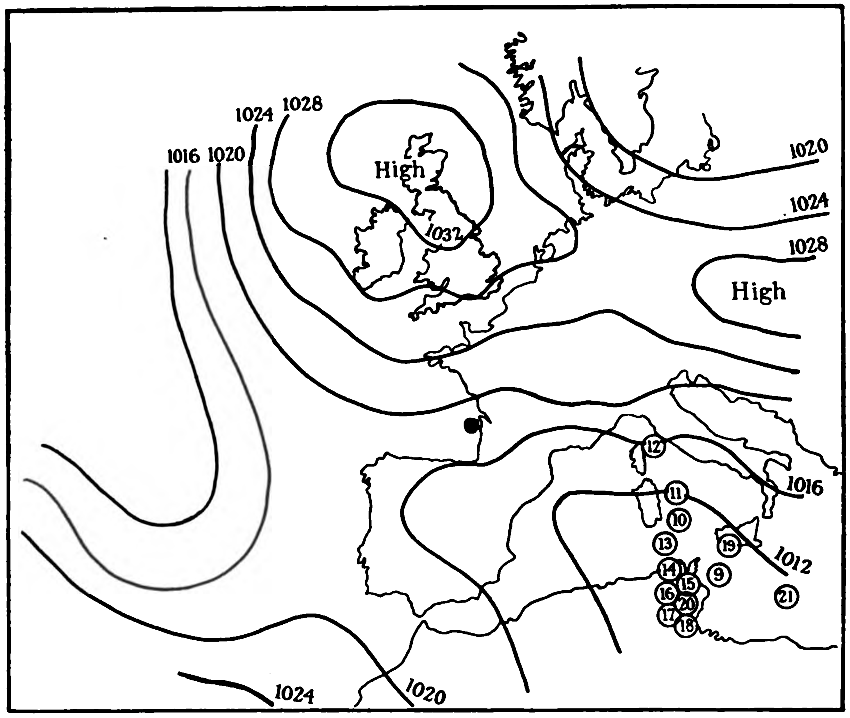

Fig. 13.—Barometric situation on the 7th November, 1924, at 1800 G.M.T. Locations from recorder intersections shown thus (1); hour of location inscribed.

Station	Position	Installed
Aldershot *	51° 15′ N ; 0° 45′ W	Dec. 1921
Lerwick	60° 10′ N ; 1° 10′ W	July 1924
Ditton Park, Langley	51° 30′ N ; 0° 35′ W	Aug. 1924
Aboukir, Egypt ..	31° 20′ N ; 33° 0′ E	Nov. 1924
Bangalore, India ..	12° 55′ N ; 77° 35′ E	Nov. 1924

Typical results.—The first test of this form of simultaneous recording has already been mentioned elsewhere,† but the results may be repeated here. The recorder at Lerwick began routine work at 10 a.m. on the 12th July, 1924. At 2 p.m. on that day the apparent directions of arrival of atmospherics at the two stations intersected off the Hebrides. The intersections of successive hourly values crossed Scotland, reached

* Transferred to Ditton Park on date shown against latter.
† Watson Watt: *Journal of the Royal Aeronautical Society*, loc. cit.

Ross-shire at 6 p.m. and May Island 9 p.m.; directions became indefinite during the night, but an intersection over the North Sea at 6 a.m. next day was followed by a series over Norway, reaching Stavanger at 1 p.m. Thunderstorms occurred at these three places near the times mentioned, the coincidence at Stavanger being exact in point of time and involving an accuracy of 2° in each bearing. The tracking continued as far as the Black Sea; in particular the apparent source lay 800 km south-east of Posen at 1 a.m. on the 14th, when a thunderstorm was in progress at Posen. The 1 a.m. location is not, however, to be regarded as directly related to the Posen storm. The series of locations was associated with a well-marked trough of low pressure crossing Europe, the trough marking the progress of a "cold front" along which air of polar origin was undercutting warm air. At 1 a.m. on the 14th July the radiotelegraphic location of a source of atmospherics still coincided with the instantaneous position of the cold front, within the close limits of accuracy with which the front could be located by synoptic data of pressure and temperature, the distance between source and receiver then being 2 700 km.

The second example is taken from the first week's simultaneous running of three recorders. On the 7th November, 1924, at 9 a.m. G.M.T., the directions of arrival of atmospherics at Lerwick, Ditton Park and Aboukir when plotted on a terrestrial globe of 50 cm diameter, intersected to indicate a source at 36° N 13° E, just east of Tunis. The successive hourly bearings over a period of 12 hours lay almost all along the meridian of 10° east, and the published meteorological data show that the trough of a shallow depression lay in this position during the day in question. Fig. 13 shows the hourly locations from 0900 to 2100 and the barometric situation at 1800.

It is hoped that a further discussion of such sources may be published when the data for the first 6 months of simultaneous recording have been examined in relation to the available meteorological data.

X. Conclusion.

A survey of the published data on atmospherics has impressed on the author's mind the complete inadequacy of sampling represented by these data, the diversity and absence of specification of the variables at the receiver, and the immense loss of value resulting from the non-coordination of the observations. The present paper has been planned to offer a description of an instrument which is certainly not the best that can now be designed, but which has proved itself capable of providing consistent data at a minimum cost. The nature of the data has been indicated by samples of three aspects; it is hoped that means may soon be found for placing at the disposal of those interested the whole of the data obtained. The instrument has already been made the basis of series of observations at stations widely distributed in the eastern hemisphere, but the network is of far too open a mesh at present. It is suggested that the time has now arrived for the organization of an international scheme, which need not absorb much labour or capital, for the collection of data on the lines indicated. The author is glad to be allowed to say that a second step in such a scheme is being taken, by the installation of two recorders of the pattern described, at German meteorological observatories.

The facilities for carrying out the work described were provided, and permission to communicate this paper was granted, by the Department of Scientific and Industrial Research, on the advice of the Radio Research Board established under that Department. Thanks are due to the Board, under the chairmanship of Sir Henry Jackson, R.N., G.C.B., K.C.V.O., F.R.S., Member, and its Committee on atmospherics, under the chairmanship of Col. H. G. Lyons, F.R.S., for their interest and advice. Thanks are also due to the staff of the Radio Research Station, Mr. J. F. Herd, Associate Member, Mr. J. E. Airey and Mr. F. E. Lutkin, and to a former member of staff, Mr. W. S. Hay, for their enthusiastic and skilful assistance in the design, construction and maintenance of the recorders and the reduction of the records, to Mr. J. Hollingworth, M.A., B.Sc., of the National Physical Laboratory, Associate Member, assisted by Mr. H. A. Thomas, M.Sc., for the calibration shown in Fig. 5, to the Air Ministry for the installation and maintenance of the recorders at Lerwick and Aboukir, and to Prof. J. K. Catterson-Smith, Member, for similar collaboration at the Indian Institute of Science, Bangalore.

[The discussion on this paper will be found on page 617.]

AN INSTANTANEOUS DIRECT-READING RADIOGONIOMETER.

By R. A. Watson Watt, B.Sc.(Eng.), and J. F. Herd, Associate Members.

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(*Paper first received 6th January, and in final form 12th February, 1926; read before the* Wireless Section *3rd March, 1926.*)

Summary.

The paper describes a visual direct-reading radiogoniometer capable of indicating the apparent azimuth of arrival of wave-trains the durations of which need not exceed 0·001 sec. The special properties of the device, which comprises essentially a combination of directional aerials with a cathode-ray oscillograph, are discussed. Amongst these properties is that of giving simultaneous bearings on two or more stations transmitting simultaneously on the same wave-length. A typical installation is described, and specimens of observations on the distribution in azimuth of received atmospheric disturbances are shown. A possible solution of the problem of navigational beacons is suggested.

I. Introduction.

The defects and limitations of radiotelegraphic direction-finders of the types in commercial use have now been clearly realized and frequently enumerated. Some of these defects are inherent in the use of the simple vertical loop as a receiving element, since multiple-ray effects are then liable to produce errors in the apparent azimuths read by the instrument. Other defects are peculiar to the means adopted for determining this apparent azimuth.

The work on which the authors are engaged, the investigation of the nature and origin of atmospherics, is peculiarly suited to call attention to these defects. The directional side of the investigation is concerned with the determination of the place of origin of electromagnetic disturbances which are arriving in very rapid succession from very diverse azimuths, from distances ranging from a few miles up to or exceeding the earth's semi-circumference, with peak field strengths varying from several volts per metre down to the lowest measurable values, with durations varying widely about a mean of the order of a few thousandths of a second, and of diverse forms.

The standard forms of radiogoniometer have been applied to the study of this heterogeneous distribution, and although the results of such applications have been very illuminating, one can only express surprise that they should have yielded data capable of interpretation.

The rotating-loop method—embracing the Marconi-Bellini-Tosi-Artom radiogoniometer with its ingenious method of rotating a large "effective loop" by means of a small search coil, the single-coil direction-finder, and the Robinson crossed-coil instrument—is not well suited for work on any signal other than a simple wave-train sustained or repeated over a period of the order of several seconds, from a sensibly stationary source, and free from interferent signals capable of producing, in the loop, electromotive forces amounting to so little as ½ of 1 per cent of the maximum electromotive force from the desired signal. The inertia of the moving elements prevents the taking of bearings on brief wave-trains, or on wave-trains the apparent azimuth of which is varying at a rate exceeding a limit which may be generously estimated at 1° per sec. The form of the cosine polar curve is such that only the position of minimum electromotive force can be used for accurate determinations, and ensures that any interferent train capable of producing E.M.F.'s of the same order of magnitude will effectively mask this minimum when the apparent azimuths of desired and undesired signals differ by 60° or more, whilst much weaker signals from azimuths within 20° of the minimum will also mask the latter. Thus it is certain that at the best this type of direction-finder will, when applied to the study of atmospherics, merely indicate the mean apparent directions of arrival of the predominant streams of atmospherics, and that there is always a high probability that two physically independent streams will be merged into one statistically true but physically fictitious stream in the indications of the instrument. When to these defects we add the extreme crudeness of the discrimination in amplitude afforded by aural reception, or by any simple recording system, it is abundantly clear that there is a pressing need for radical changes in direction-finding apparatus in general, and in that used in the study of atmospherics in particular.

The ideal radiogoniometer would record the true azimuth of arrival, i.e. the horizontal projection of the direction of propagation at the point of incidence on the receiver, of any desired signal, of whatever form or magnitude, and however brief its duration, and would at the same time record at least one fundamental parameter determined by peak field strength or one of its derivatives. The indication should be independent of the presence of simultaneously incident signals of any form or distribution.

The purpose of the present paper is not to describe the ideal instrument, but to describe a device which is believed to be a much closer approximation to that ideal than were its predecessors.

II. Description.

The general principle of the device is almost too simple to require detailed notice. Consider, for example, two loop aerials, A and B, identical in every respect, with their planes vertical and at right angles to one another. Then a vertical wave-front, in which the maximum vertical electric force is E, and the ray direction of which makes an angle ψ with the plane of loop A, will produce E.M.F.'s proportional to $E \cos \psi$

and $E \sin \psi$ in A and B respectively. The E.M.F.'s across the identical capacities C_A and C_B will have the same ratio. Let the two perpendicular and identical deflector systems, ns and ew, of a cathode-ray oscillograph be connected across C_A and C_B respectively. Assuming for the moment that the deflectors have their centre points in a plane perpendicular to the axis of the undeflected beam, the two fields will recombine to produce a resultant field of strength proportional to E, and making an angle ψ with the axis of deflection corresponding to plates ns. Thus the fluorescent spot traces on the screen a line the length of which is linearly related, through the intervention of simple circuital constants, to the E.M.F. which would be induced in a loop, similar to loop A, with its plane in the ray direction; this E.M.F. in its turn is proportional to the rate of change of electric force in the wave-front, and is related to that rate of change by the well-known equation of the loop antenna. Further, the angle which this fluorescent line makes with the reference axis ns is equal to the angle between the ray direction and the plane of loop A.

Similar considerations apply in the case of magnetic deflection, but in general it is desirable to operate by electrostatic deflection, since the impedances involved are usually of an order which enables greater sensitivity to be attained by this method.

If sensitivity comparable with that of the standard direction-finding installations of commerce be required, then in general the component electromotive forces induced in the two loop aerials will require amplification before being applied to produce deflecting fields in the oscillograph system. It will be shown later that this amplification can be successfully employed.

In passing from the ideal case to the actual apparatus, employing the type of oscillograph mentioned, several minor points are to be noted. In the first instance it should be observed that in the instrument used the disposition of the deflector systems is as in Fig. 1. The change of field during the time occupied by an electron in traversing the paths between either pair of deflectors, or from the one system to the other, may be neglected, since the total path xy is executed in 0·0015 microsecond, corresponding to a phase angle of $\frac{1}{2}°$ at a frequency of 1 million per second, so that no error is introduced from this cause, even at the shortest commercial wave-length now in use. For still higher frequencies the re-design of the oscillograph to reduce this time-lag to negligibility does not appear to present serious difficulty.

A second point arising from the same feature of the tube design is that whilst the angular deflection produced by unit E.M.F. in the two systems is the same, the plates producing horizontal deflection are nearer the screen than are those producing vertical deflection, the distance ratio being 1·08. There is consequently an angular error which varies with azimuth, reaching a maximum of $2\frac{1}{4}°$ around the 45° points. As this source of error is independent of amplitude and frequency, a permanent scale correction is readily applied when necessary. Again the error is not inherent in the system, but is incidental to the particular instrument used. In any case it can be compensated by a method to be mentioned later.

In cases, such as the study of atmospherics, in which there is no possibility of even a rough check on the faithfulness of the indications, it is desirable to eliminate even remote possibilities of error. For this reason the installation at Ditton Park, to be described, is by no means the simplest or cheapest that can be realized within the scope of the general principle of making an ionic beam the self-setting moving element of the goniometer. It is, however, based on circuits which most completely satisfy the requirements of symmetry and freedom from risk of unequal amplification of the component electromotive forces.

The circuit of this typical installation is represented in Fig. 2. The receptive system comprises two loops in two vertical planes intersecting at right angles along a line bisecting the horizontal sides of each loop. To ensure freedom from "antenna effect" or "vertical," the mid-points of these horizontal sides are all connected to earth, as is also the anode of the oscillograph. The tuning devices—loading inductances if required, and tuning condensers—are split and arranged symmetrically on either side of the central earth lead. There are

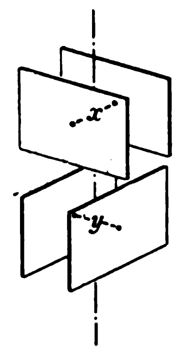

FIG. 1.—Deflecting plates of cathode-ray oscillograph.

consequently, in each main loop, two tuned half-loops, the tuning of each half being nearly independent of the tuning of the other. Carrying still further the provision for complete symmetry, special oscillographs have been obtained in which each deflecting plate is separately terminalled. It will be noted that in the standard pattern of oscillograph two of the plates are joined directly together and to the anode, whilst the other two, one of each pair, are joined to the anode through external resistive paths, so that complete symmetry is not attainable with this form of tube.

In the case of strong signals the oscillograph deflecting-plates may be connected directly across the tuning condensers as shown in Fig. 2. For weaker signals the general scheme of single-stage or multiple-stage amplification is illustrated in Fig. 3. Since the load impedance of the oscillograph, with its plate-to-plate capacity of about 10 $\mu\mu$F and its gaseous conduction path of about 2 megohms, is high, the conditions are especially suitable for "voltage amplification" by a resistance-capacity amplifier employing triodes of high voltage factor.

It will be seen from Fig. 3 that symmetry is maintained by using a circuit of the so-called "push-pull" type, in which (considering only one stage) the filaments

are connected to the central earth lead, whilst the grids are each connected to the high-potential sides of the tuning condensers in the half-loops. The oscillograph deflecting plates are joined through coupling condensers to points on the high resistances included in the plate circuits.

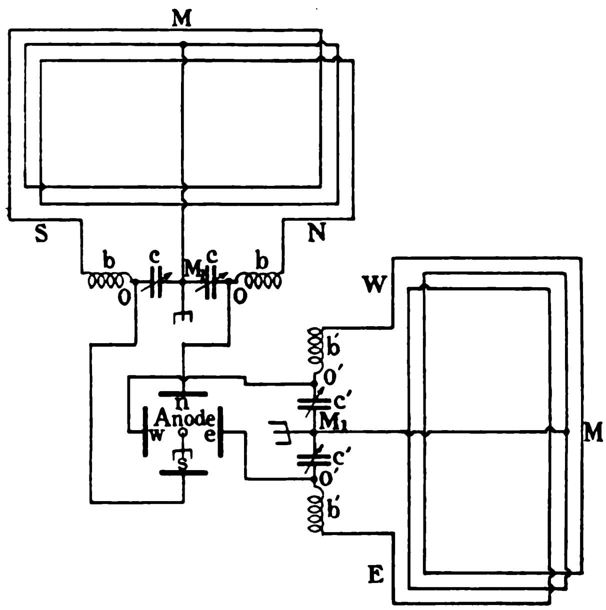

FIG. 2.—General arrangement of cathode-ray direction-finder.

In the actual installation under description, the loops are supported on a mast system comprising a central wood lattice mast 200 ft. high, and four wood box masts 150 ft. high, at the corners of a square of 1 200 ft. diagonal. Each loop comprises five turns, which can be grouped in series or parallel, each turn measuring

at about 10 kilocycles, comprises a coil of 136 mH and an air and mica condenser assembly with a maximum capacity of $0\cdot006\ \mu$F. The arrangement of these units will be referred to later.

The amplifiers are based on the use of the D.E. 5B triode, and with anode resistances (wire wound) of 10^5 ohms, and plate circuit voltage 300, give a voltage magnification of 15 per stage. The first anode resistance in each side is tapped approximately in thirds, so that the available voltage magnifications are 5, 10, 15, 75, 150 and 225.

The oscillograph has a deflectional sensitivity of 1 mm per volt, so that the sensitivities of the combination of amplifier and oscillograph are 1 mm for 200, 100, 67, 13, 7, and 4 millivolts respectively on grid. Full-scale deflection, reaching the outer edge of the oscillograph screen, amounts to 50 mm, the angular scale value then being $0\cdot87$ mm per degree of angle. So far as reading goes, therefore, accuracies of 1° can be attained on any deflection exceeding half scale.

The two special features of this installation are the precautions taken to ensure symmetry, and the large areas of loop used. This latter feature is part of a general policy which has guided all our quantitative work on atmospherics, namely that the antenna system should be of such dimensions as to allow measurements to be made with a minimum of amplification. It is a general experience that quantitative uncertainties increase rapidly as amplification is increased, and for fundamental work the more antenna and the less amplifier the better. It must not be thought, however, that acres of antennæ are essential to the system, nor that the somewhat uneconomical duplication of triodes, giving only a doubling of amplification, in the push-pull system is inevitable. The use of loops the individual turns of which have an area of 30 m², with one pair of vertical sides coincident, in combination with normal amplifiers and the standard form of cathode-ray oscillograph, has already been shown to be practicable,

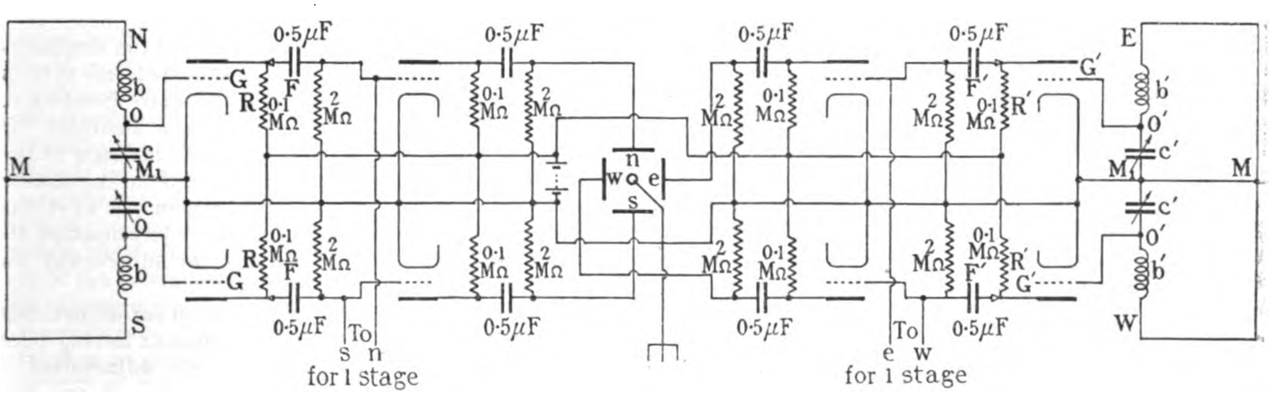

FIG. 3.—Details of circuits.

1 200 ft. horizontally by some 150 ft. deep, the area-turns in the series grouping being thus about $8\cdot4 \times 10^4$ m² (about 20 acres). The inductance of the series arrangement is 19 mH, and the effective resistance at 10 kilocycles is 200 ohms. Each unit of the tuning system, as used for atmospheric observations

and further wide modifications should result from systematic development work, which has not been required for work on atmospherics but is desirable for the production of a compact visual direction-finder for general use.

The principal conditions to be fulfilled by the system

refer particularly to the amplifier and the oscillograph. The amplifier should give a distortionless linear magnification, without rectification, over a range of $\pm$ 50 volts output, unless an oscillograph more sensitive than the standard 300-volt pattern is used. There is room for some very interesting work on amplifiers specially adapted to meet these conditions when working into such a high-impedance terminal apparatus as the oscillograph. Such work has been begun, but need not be discussed at present. It should, however, be noted that the previous visual direct-reading radiogoniometer due to Artom involved rectification, which results in the introduction of further ambiguities in addition to the ordinary radiogoniometric ambiguity of 180°, since it gives bearings which are concentrated in one quadrant, so that there is no distinction of a given bearing from its image with respect to one of the principal axes, giving a fourfold ambiguity when the non-discrimination of sense is taken into account. In the present device the only ambiguity is that of sense, and it can be resolved by methods already used in radiogoniometry, and also by methods peculiar to the oscillographic arrangement.

The conditions to be fulfilled by the cathode-ray oscillograph are not, except in respect of the one point already discussed in relation to the different distances between screen and deflecting systems, different from those to be fulfilled by a general-purpose oscillograph. These are, summarily: (*a*) That the indicating spot shall be small, symmetrical and sharply defined, and shall remain so at all velocities of deflection; (*b*) that the deflections shall be linearly related to the applied field over the full range of the screen; (*c*) that the axes of the two deflecting systems shall be strictly at right angles; (*d*) that the deflectional sensitivity shall be as high as possible; (*e*) that the fluorescent material shall give the most brilliant response possible to the lowest electron speeds and densities used; and (*f*) that the life of the instrument shall be as long as possible.

It is a truism to say that the cathode-ray oscillograph as a general laboratory and industrial tool is in its infancy, since the inconveniences of the older forms have only recently been removed. Rapid improvement in quality and uniformity of the product may be expected to accompany increased demand, and it is significant that nearly half the November issue of the *Journal* was devoted to this instrument. Recent work * has resulted in the production of an oscillograph with a sensitivity of nearly 1 cm per volt, and work initiated by the Radio Research Board has shown that very considerable improvements in fluorescent screens for visual work are within immediate reach. The future of the cathode-ray direction-finder is intimately linked with the progress of the cathode-ray oscillograph, and must not be judged alone on its performance with existing oscillographs, good as that performance is.

It is clearly necessary that provision should be made for the tuning, testing and adjustment of the radiogoniometer system, and the arrangements adopted at Ditton Park will serve as an illustration of this provision. When the whole system is correctly tuned and adjusted, the arrival of a sustained signal of the selected frequency causes the indicating spot of the oscillograph to trace a straight line which makes with the two principal axes—representing the deflections due to the two pairs of deflecting plates acting independently—angles which are the angles between the direction of arrival of the signal and the planes of the corresponding aerials. The effect of slight mistuning is to open this straight line into an ellipse, since the spot is now under the control of two misphased fields. This opening to an ellipse is a very sensitive index of mistuning, and is, in the case of "single ray" propagation, at least, an effective safeguard against errors of bearing due to bad tuning. The ellipse is quite wide before its major axis begins to depart by a measurable amount from the correct angle. This tuning operation may be performed directly on the signal, or it may be performed on locally generated oscillations of the desired frequency. A screened, calibrated oscillator is coupled to a testing instrument in which the main loading inductances already mentioned form the secondary windings of a crossed transformer, the loading coils belonging to one loop being coaxial and having their common axis at right angles to the common axis of the coils belonging to the other loop. The primary is a coil capable of rotation about an axis in its own plane perpendicular to these axes, and is fed from the oscillator. The system is in fact similar to the crossed transformer of the Bellini-Tosi radiogoniometer, the search coil being excited and inducing into the field coils, instead of the inverse operation as in directional reception. The primary may first be coupled to one loop alone and this loop tuned up, then the other loop may be tuned independently; finally both may be tuned to identity as tested by the closing of the ellipse. If, as may happen, the operation is complicated by the presence of signals, the loops may be replaced by dummy circuits of the same inductance and resistance. This instrument also permits the testing of the voltage amplification on each side of the system. In the ideal case these amplifications should be identical, but in practice circumstances may call for a ratio differing from unity. For instance, the difference in distance from screen to deflectors, already mentioned, is most easily corrected by the increase of the amplification factor on the side connected to the deflector system nearer the screen, until the deflections corresponding to identical inputs to the two systems are identical. It will be seen that as the only convenient measure of the relative amplifications is by length of line on the screen, the operator is not required to remember anything about this correction *per se*—its compensation is automatically included in the general adjustment for amplification.

The methods of determining the need for adjustment of amplification and for testing its amount having been indicated, it remains to show how the adjustment is performed. The method may of course vary according to the typle of amplifier in use, but there is probably no more simple and satisfactory method for general purposes than the provision of a variable tapping of the anode circuit resistances in one stage of resistance-capacity amplification, so that the proportion of the whole voltage released across this resistance which is transferred to the oscillograph or to the next grid may be varied over wide limits. Preliminary selection of matched triodes

* BUCHTA: *Journal of the Optical Society of America*, 1925, vol. 10, p. 581.

then ensures that very little correction is necessary in most cases, whilst the correction even of large divergences can be effected.

III. Properties.

In its application to signal work the system has many interesting and attractive properties which are believed to offer considerable advantages over earlier systems, and a brief enumeration of some of these may be permissible.

Some outstanding advantages have already been described in sufficient detail to show that the device will provide an automatic visual and direct-reading radiogoniometer, capable of operation by the navigator on the bridge or in the chart-room, without requiring a knowledge of morse, and that it will deal with signal trains of exceedingly short duration.

Attention has not yet, however, been called to one of its other outstanding advantages. The difficulties of direction-finding in cases of even slight jamming are well known. The cathode-ray direction-finder alone has the valuable property that it will give correct bearings, simultaneously, even in the extreme case of two or more signals of the same frequency and the same field strengths arriving from different azimuths during the same period. That this is so will be seen from the fact that the ionic beam gives instantaneous response to every impulse, so that if a marking impulse arrives from one transmitter while the other is spacing, the beam will trace out a line having the bearing of the former transmitter, and conversely. There are three types of pattern which may be obtained in practice. If the stations are working independently at hand speed, then the marking periods in both cases are interrupted by comparatively long spacing gaps, during which many marking impulses from the other station will arrive. The predominant features of the image on the fluorescent screen will then be two bright lines, each indicating the correct bearing and amplitude of the corresponding signal, and standing out perfectly clearly from a background of faint fluorescence. If the stations are working independently at high speeds with very brief spacing periods, then the pattern becomes a parallelogram full of fluorescence the clearly defined sides of which are respectively parallel to the two required bearings, and of lengths proportional to the two signal strengths. The faint background referred to in the first case is also a parallelogram of this type. The clear definition of the edges of the figure is of course due to the fact that each point on them is a stationary point on the high-frequency path of the indicating spot, and has therefore a relatively long exposure, giving correspondingly greater brilliance of fluorescence. Lastly, in a case which is never likely to be met in practice, if the two transmissions are not independent but fed from the same source, then the pattern becomes a generalized Lissajou figure, from which the two bearings may be inferred. Excluding this case, however, it is seen that in the worst practical case of jamming, two identical stations sending identical text, on identical frequencies and with identical field strengths, the two bearings are still read directly and easily. Increase in the number of the jamming stations merely increases the complexity of the image. With three high-speed stations, beyond which we have not had an available jamming mixture on which to test, the three bearings are still easily read simultaneously.

The next application of the special properties of this device which calls for mention is that to the wide general class of "bad minima" so troublesome in the older

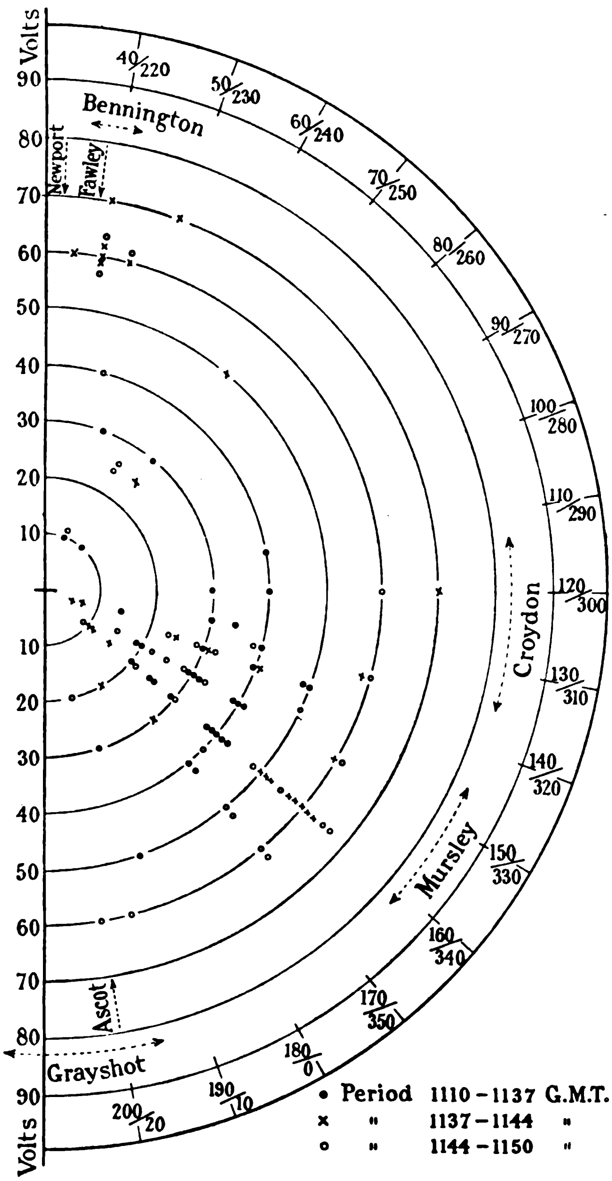

Fig. 4.—Azimuthal distribution of atmospherics and thunderstorms on the 10th May, 1925.

systems. The cathode-ray direction-finder, with its freedom from inertia effects and its discrimination in amplitude, will throw light on the particular cause of bad minimum which happens to be operative in any given case, and will in very many cases allow a determination to be made, with a direct measure of its probable error, in cases where otherwise no measurement at all could be made or relied on. Thus the flickering bearing due to intermittent contacts in metallic rigging will

give a measurable sector of swing of the fluorescent trace, probably accompanied by the elliptic opening indicating dephasing of one aerial, and the phenomena of night effect will be delineated in detail.

IV. Typical Observations on Atmospherics.

The first decisive test of observations on atmospherics with the device described was made on the 5th May, 1923. Between 2000 and 2300 G.M.T. on that date thunderstorms were in progress in Yorkshire and other northern districts, and the lightning of these storms was visible at Aldershot; this lightning varied in azimuth between N.N.W. and N.N.E. Simultaneous determinations of the apparent azimuth indicated by the cathode-ray direction-finder and of the azimuth of the visible lightning showed in a large majority of cases agreement within 5°, which was approximately the limit of estimation in the direct observation of the somewhat faint and diffuse glows produced on the horizon by the distant flashes. The failures were due to the complex screen image produced in the direction-finder by relatively near discharges. The direction-finder also provided azimuthal determinations for a very large number of discharges for which no corresponding visible lightning was observed.

More recent samples of the discriminating powers of

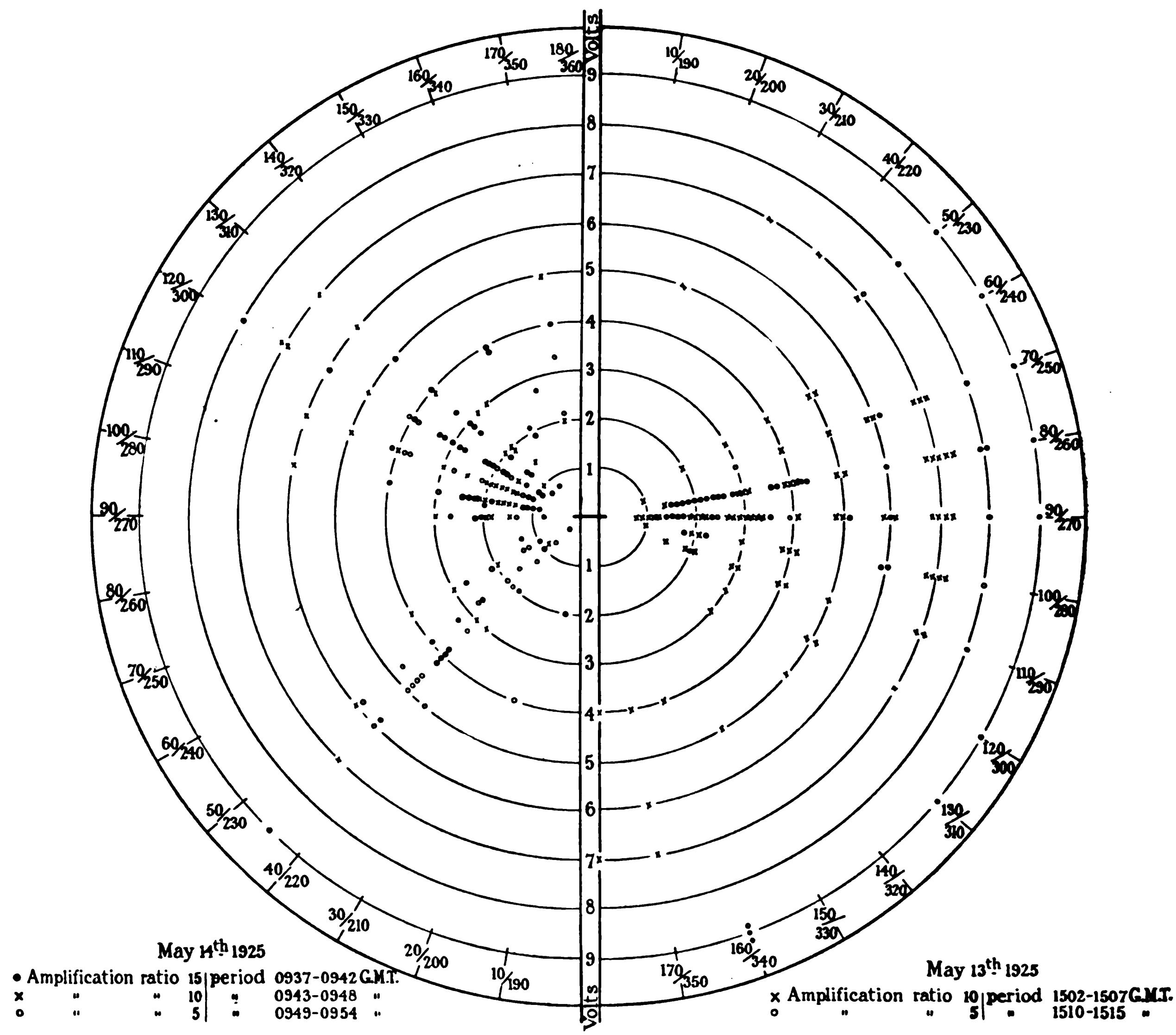

Fig. 5.—Azimuthal distribution of atmospherics on the 13th and 14th May, 1925.

the device may be cited, with reference to Figs. 4 and 5. In these figures are plotted polar co-ordinates representative of individual atmospherics, the angular position indicating the apparent azimuth, with its ambiguity of 180°, the radius vector the voltage produced across the tuning condenser in the apparatus described. No more fundamental measure of the intensity of the atmospheric can, in the absence of data as to the wave-form of the individual discharges, readily be given. The observations of Fig. 4, made without amplification,

correspond to an oscillographic scale value of 10 volts per cm, those of Fig. 5 to scale values varying, with the amplification factors used, from 0·7 volt to 2 volts per cm. These are all plotted to a uniform voltage scale.

Fig. 4 represents observations on the morning of the 10th May, 1925, between 1110 and 1150 G.M.T. On the conclusion of the observations, examination of the sky showed thunderclouds at the approximate azimuths 340°, 240° and 120° E. of N., the most formidable being that at 340°, the least that at 120°. It will be seen that the most disturbed direction is that of the principal cloud, and that disturbances appear to have arrived from all three clouds, though no thunder was heard at the Radio Research Station. Subsequent examination, however, showed very complete agreement between observed thunderstorms and the apparent azimuths of arrival of atmospherics. There have been plotted in Fig. 4 the results obtained by assuming thunder to be audible up to a distance of 12 miles from the station reporting it, and plotting the arc subtended by a line extending for 12 miles from meteorological stations in the direction in which thunder was noted by the meteorological observers. The arcs thus delimit the azimuthal regions from which atmospherics would have been expected to arrive. The main disturbance is seen to have originated in a thunderstorm reported from Mursley, Bucks (S.W. at 1040 to N.E. at 1230). The next most important source was the thunderstorm reported from Bennington, Herts (N.E. at 1100), whilst disturbances were also received from thunderstorms near Croydon (S. at 1123), Ascot (1130 to 1230), and Grayshott (W. at 1145). Two of the clouds seen probably belonged to the Mursley and Croydon storms; the third, producing the discharges from 60°–240°, has not been traced in thunderstorm reports.

For comparison with Fig. 4, Fig. 5 presents data of the distribution at two periods, 19 hours apart, in neither of which was thunder reported in England, Wales or Ireland. It is of interest to note that, despite this absence of near reported thunder, E.M.F.'s of 4 volts and over were produced across the tuning condenser of 0·001 μF in the aerial circuit (cf. page 613) tuned to 12 kilocycles.

V. The Beacon Problem.

The sum of these special properties has, in the authors' opinion, a very important relation to the vexed question of the navigational radiotelegraphic beacon. The problem posed is the provision of a network of beacons which, while sufficient for position-fixing by directional wireless observations, must produce the minimum of interference with other radiotelegraphic traffic. Were the cathode-ray direction-finder adopted as the standard instrument for observation on beacons, what form of beacon would be required? A continuous-wave transmitter modulated m per cent with a frequency f, is the generally accepted beacon in all cases, but the authors believe that the important fact is that for observation by the cathode-ray direction-finder f need only be a fraction of 1 cycle per second, m can be made large, while both m and f can be given values which become characteristic of a series of beacons. The beacons may work continuously and simultaneously on the same narrow wave-band, and the form of the modulation may be made such that the period of sensible amplitude is relatively very brief. The form of a typical screen image in a direction-finder taking a cross bearing on two beacons might then, for example, consist of two lines intersecting at an angle of 55°, one varying once in 3 seconds from full length to half length, the other once in 5 seconds from full length to quarter length. The navigator reads the two bearings, finds in his list the stations characterized by $m = 50$ and $f = 0{\cdot}33$, and by $m = 75$ and $f = 0{\cdot}2$ respectively, and the problem is solved. It is admitted that the scheme involves wide organization, but wide organization, reorganization and control will in any case be enforced by the seriousness of the problem of interference prevention.

The facilities for carrying out the work described were provided, and permission to communicate this paper was granted, by the Department of Scientific and Industrial Research, on the advice of the Radio Research Board established under that Department. Thanks are due to the Board, and to its Committees on atmospherics and directional wireless, for their interest and advice; and also to the Director of the Meteorological Office for the data used in Section IV.

Discussion before the Wireless Section, 3 March, 1926.

Admiral of the Fleet Sir H. B. Jackson: I have had the opportunity of watching the progress of this work during the past few years. At its commencement amplifiers were not in their present high stage of development, and the amplifier alone was one of the things which took a very considerable time to design. I think it will be admitted, however, that, judging from the results obtained, the design which has been retained all through has been satisfactory. The same remark applies to the other details of the apparatus described, which has now been thoroughly tested and is giving satisfactory and valuable results.

Dr. G. C. Simpson: In common with Sir Henry Jackson, I have seen practically the whole of this investigation; in fact it began under the Meteorological Office. One aspect of the work is the meteorological side, and this is again divided into two. There is the actual practical use of this apparatus for meteorological work, which I hope Mr. Giblett will explain later in the discussion, and there is the theoretical side. When this work started we had not the slightest idea of the origin of these atmospherics, i.e. as to whether they came from the upper atmosphere after some electrical discharge, whether they were connected with the aurora or with electrical storms; in fact we were not certain that they were terrestrial at all. At the same time we did know that there were atmospherics connected with thunderstorms, and although early in the work Mr. Watson Watt came to the conclusion that all atmospherics were due to terrestrial thunderstorms,

personally I did not feel that that was likely. I doubted whether there were sufficient thunderstorms in the world to supply these atmospherics, but as the work progressed I gradually became converted to the opinion that all these atmospherics do arise as the result of lightning flashes in some part of the world. If we can prove that, I think it will be a very great advance, because there is no doubt that it will help very much in our efforts to guard against atmospherics, and to apply the results of this work to radio telegraphy, when both the source of the atmospherics and the reasons for them are known.

Prof. J. T. MacGregor-Morris: The author of the first paper points out that in the revolving-coil apparatus only the resultant direction of atmospherics coming either in one direction or in the diametrically opposite direction are recorded at any one instant; it is, however, possible that the component at right angles might be simultaneously recorded. Suppose two coils are fixed at right angles to one another so that they rotate together, and that a duplicate of the arrangement used with the first coil be connected to a second Bloch oscillograph; then the pens of these two recorders could be so arranged that they could operate very near to the same spot on the drum. Red ink could be used in one and black ink in the other. If I am right the records will give the resultant of the atmospherics in one direction and their resultant at right angles at any instant. One should therefore be able to deduce from the two simultaneously obtained records, the direction and strength of any atmospheric by taking the resultant of those two points. I admit that this complicates the apparatus, and the author has been definitely working to make the apparatus as simple as possible. However, it is for those who are directing the work to consider whether the complication is justified.

With regard to the second paper, I should like to submit that the term "electron jet" be used in preference to "cathode ray." I quite realize that in the past the term "cathode ray" has been universally used; but now that we understand that it is primarily a jet of electrons I think it would be helpful to call it an "electron jet." The authors call attention to the fact that the two pairs of plates in the Western Electric cathode-ray oscillograph shown in Fig. 1 are at different distances from the recording plate, and so are unequal in their recording sensitivity. One possible method would be to split the A-phase plates in half and arrange so that the electron jet first traversed the first half of the A-phase plates, then the complete B-phase plates, and finally the second half of the A-phase plates. With regard to the fluorescent screen, a good deal of work has been done recently in improving this, and I should be glad if the authors would give some information as to the improvement which has been made during the past two years, because a great deal depends on the sensitivity of the screen. Quite recently in America these tubes have been used with quartz plates at the end, so that a photographic plate placed in contact with the quartz plate requires only an extremely short exposure. I am not clear why the apparatus was adjusted to a periodicity of 10 000 cycles. I do not think anybody would say that all lightning flashes had this frequency. Is it not possible to have another circuit in parallel with the first circuit, tuned to another frequency, so that both are operative on the same plates? This would enable records due to the two to be obtained. Another point is with regard to the making of this apparatus so that it is photographically continuously recording. Is it worth using two of these oscillographs and losing the simplicity of this polar diagram? Only one pair of plates must then be used in each, with a quartz slip at the end of the bulb so that the ray simply travels backwards and forwards in each of the oscillographs, letting the ray shine on the photographic film, the two pairs of plates being connected to two frame coils at right angles. If these photographic films are continuously recording it will then be possible, from the readings of the two films, to combine them at leisure.

Mr. R. H. Barfield: Although the first paper nominally describes only the construction and working of an instrument, the masses of observational data which are dealt with in it throw an interesting light on the nature and magnitude of the work on which Mr. Watson Watt and his staff are engaged in their systematic study of atmospherics and must, I think, arouse a considerable amount of admiration for the scientific and persevering nature of their attack on this problem. As regards the instrument itself, by paying attention to every detail of its design Mr. Watson Watt has constructed an elaborate piece of mechanism which, as he has demonstrated, fulfils a relatively novel purpose with complete success. Mr. Watson Watt shows that it is possible to gain from the records of this instrument a certain amount of information regarding the intensity of the atmospherics received. Has he ever found any confirmation of the effect described in some detail by Dr. Eccles in the *Proceedings of the Royal Society* (1912, vol. 87)? Dr. Eccles here records that he observed quite regularly over a prolonged period a marked diminution in intensity of all atmospherics for about a minute at the hour of sunrise, and gives a plausible explanation of this phenomenon based on atmospheric ionization of solar origin.

Squadron-Leader E. L. Johnston: I propose to discuss the papers from the point of view of the navigator. With the advent of wireless direction-finding apparatus an entirely new method of navigation has been achieved, and I claim that it is not too much to say that this branch of science will completely revolutionize the practice of navigation in the very near future. In particular, wireless direction-finding is of the greatest importance to fast-travelling aerial transport on transcontinental and transoceanic flights.

I have come to the conclusion that the radiogoniometer described in the second paper is an instrument which may be second to none in its importance to navigation and that it more nearly approaches the conception of a "wireless compass" than any other apparatus developed on the principle of wireless direction-finding. In discussing the beacon problem the authors say that the navigator reads the two bearings, finds in his list the characteristics of the periods of the beacon stations and the problem is solved. If that were so, there would be no further need for navigators. It is not generally recognized that science, employing

the mathematician and the engineer alike in the problem of shortening the duration of transcontinental and transoceanic transit, has accomplished as much by causing the vehicles of transit to travel fewer miles as by causing them to travel faster. In this age of aerial transit the route of minimum distance and the determination of position by long-distance wireless telegraph bearings is coming to take the place which was held by the route through regions of favourable winds and free water and the determination of position by observations for latitude and longitude by means of celestial bodies as in the days of sail and steam propulsion. By increasing the rate of travel, modern motive power, by making possible a departure from the old meteorological routes, has had another and greater effect in the progress of the universal policy of civilized nations to accelerate transit from place to place to the utmost possible extent, because aircraft may yet get further toward their destination in a given time since they may be navigated along the arc of the great circles of the earth. The increasing recognition among navigators of the sound principles of navigating along the arc of the great circle, and the expanding sense of the advantages to be gained by a knowledge of this branch of the science of navigation, have greatly enhanced the value of methods which place the benefits of the knowledge and use of the great-circle track at the service of the navigator without the labour of the calculations involved in the practice of great-circle sailing. The general lack of the application of the principles of the great circle in the past seems to have resulted not from the want of recognizing that the shortest distance between any two places on the earth's surface is the distance along the great-circle arc passing through them, nor that the great-circle course is the only perfect course and that the courses steered by the magnetic or gyrostatic compasses are circuitous, but to the tedious operations which have been necessary for rendering these benefits available. The rhumb line, or the line of constant bearing, which is that steered by the magnetic or gyrostatic compass, although appearing on the Mercator projection as a straight line, gives a false idea that it represents the shortest route, and is in reality a roundabout track. The great circle on the other hand appears on the Mercator projection as a curve, concave towards the pole and, whilst being actually the shortest distance, appears as a roundabout way. It crosses the meridians, however, at a constantly changing angle and therein lies the great drawback in its application to everyday navigation. The navigator is then supposed to conduct his craft by one of two methods: (1) He is supposed to follow a simple line, the rhumb, and go the longest way about, or (2) he is supposed to go the shortest way, by the great-circle arc, and endeavours to follow a complicated curve. The navigator, however, being a practical man, does neither. He first of all finds out how much his rhumb-line distance differs from the great-circle distance, and, if the difference is sufficiently considerable to have any material effect upon the length of his journey, he approximates his great circle by a succession of rhumb lines which are chords to the great-circle arcs. But now we have this cathode-ray direction-finder which gives a visual indication on a graduated dial of the bearing of a transmitting beacon station, and therefore, provided that the place of destination is equipped with a beacon station and that it transmits at sufficiently short intervals, it would appear that the navigator only requires to steer his craft in the direction of the fluorescent ray and the result would be that he would follow the great-circle arc and thus take the shortest route. The installation of beacons to fulfil this function on every route would, however, be a very costly business and would probably be prohibitive on those grounds. Therefore, for some long time yet the navigator will have to make use of whatever wireless telegraph stations are available, and it is highly improbable that he will always be fortunate enough to have a wireless telegraph station at his destination to guide his passage, nor would it, if this condition were fulfilled, transmit at sufficiently short and regular periods to enable him to steer a great-circle track. Some auxiliary means of steering would be necessary. The next thing then is to make use of the instrument for position-fixing by means of cross bearings. Let us consider the question of position-fixing by means of wireless bearings. Mercator's projection, as perfected by the English scientists, Bond and Wright, is the most suitable for the solution of the everyday problems which confront the navigator, but unfortunately the great-circle bearing cannot be laid off upon it as a simple straight line without the application of the angle of half convergency. If, then, the navigator is going to make use of the cathode-ray direction-finder, he will wish to have a projection which will show all the great circles as straight lines so that they can be simply laid off. The gnomonic projection is the one which most nearly fulfils his requirements, inasmuch as all great circles are projected as straight lines, but unfortunately the orientation of the bearings is only correct from the tangential point of the projection and there cannot be any constant linear scale on it. From the foregoing I trust that I have made it sufficiently plain that instead of the problem of navigation being solved by the use of the cathode-ray direction-finder, the navigator's work really only begins at its introduction.

Mr. M. A. Giblett: Dr. Simpson has already mentioned the subject of the meteorological applications of the author's apparatus. The practical application to which he referred was the application to the meteorological protection of the proposed long-distance airship routes to Egypt and India. The one meteorological phenomenon of which we have to take great notice in the case of airship navigation is the thunderstorm, not so much because of the electrical phenomena but because of the strong associated vertical atmospheric currents. It will therefore be very necessary to include in the meteorological organization for those long-distance routes some means of keeping track of all thunderstorms and similar disturbances. It would hardly be possible even with unlimited funds to have ordinary ground observing stations sufficiently close to keep all thunderstorms under observation. Therefore I think that the author's apparatus does open up possibilities. By using a few thunderstorm directional observing installations at various points along the route, the observers' visual horizon could be extended

to areas where no ordinary meteorological observing stations can be placed. In addition to the use of such apparatus on the ground, I think it would also be useful if it could be arranged to have such an apparatus in the airship herself, because the meteorological organization would be divided between a ground organization which would pass general advice to the airship, and a minor organization in the airship herself for co-ordinating the information received from the ground. The ground organization would give general information as to the disturbed areas on the whole route. Such an apparatus on the airship herself would begin to function when the airship approached one of those disturbed areas, and would be used for short-range work in circumnavigating them. There is another meteorological aspect of this work. In modern meteorology it has become general to link up everything we can with what is called the "polar front." The "polar front" may be visualized, very much simplified for present purposes, as the battle-front between cold air currents of polar origin and warm air currents of tropical origin, the one striving to go south and the other to go north. The battlefield may be visualized as a chain lying round the northern hemisphere, being composed of links of three different kinds, links where neither side is gaining, links where the cold air is gaining southwards, and links where the warm air is gaining northwards. Those three links have certain different characteristics. Where the "front" is stationary nothing very important happens; where the warm air is going northwards there is in general a gradual ascent of that warm air over the cold; but where the cold air is gaining ground there are often very strong vertical currents. The cold air undercuts the warm air and pushes it up violently. It will become, therefore, very important for the meteorological advisers to the airship pilots to indicate where these various links are and how they are moving. The "polar front" often lies south of the British Isles, and therefore an airship flying from India to England will very frequently have to cross it; and the question arises as to what route the pilot must follow in order to cross the "polar front" in the easiest and safest manner. The best way to cross it is where the "front" is stationary; the second best is to cross it where the warm air is gaining, but as the third link may sometimes be 700 to 1 000 miles long it may have to be crossed or a delay incurred. For meteorological reasons it is difficult at present to say exactly how intense these vertical currents are in that link on any particular occasion. We know sometimes they are very bad indeed. The recent airship disaster in America occurred on such a "front" where the vertical currents were strong. On the other hand, airships have passed across this link in the "polar front" with safety, and the design of future airships will of course take into account the magnitude of vertical currents which may be met. I suggest that Mr. Watson Watt's apparatus may give us some means of picking out the really violent parts of this "polar front." French investigators, headed by M. Bureau, actually claim that the links of this chain where the cold air is gaining are fruitful sources of atmospherics, whereas the other two kinds of links do not give rise to atmospherics at all. It might therefore serve a very useful purpose if Mr. Watson Watt were to put that to the test with the data which he has accumulated, and if he were to investigate whether there is any proportionality between the intensity of the "fronts" as regards vertical motion and the intensity of the atmospherics. If so, there will be a very practical application of this apparatus to aerial navigation.

Mr. E. H. Shaughnessy: I gather that generally the result of Mr. Watson Watt's work is to show that there is a relation between meteorological conditions and atmospheric conditions as we know them in wireless telegraphy. I do not think, however, that the determination of that relation can be claimed as being due to the use of the cathode-ray apparatus which has been described. Probably any good direction-finding apparatus might have been able to show the place of origin of atmospherics. I understood that the cathode-ray oscillograph circuit was tuned to 10 kilocycles, and a very interesting direction-finding result on Rugby and Leafield obtained. It seems to me that that case shows a serious defect, as the plot on that result being so indefinite does not inspire confidence in that particular direction-finder as compared with other well-known and well established direction-finders. Is it not possible with this set to cut out one station from another? With an ordinary direction-finder working on Rugby there would be no difficulty in cutting out Leafield from Rugby.

Dr. R. L. Smith-Rose: On page 603, in the first paper, in referring to the accuracy of discrimination of the automatic direction-finder, the author seems to have some doubt as to whether the accuracy of 2° associated with the instrument itself may have any meaning practically when dealing with the apparent direction of arrival of the atmospherics. I have had some considerable experience in observing the apparent directions of wireless signals, and from the analysis of data on this point I think it possible to draw some conclusions which should be very consoling to Mr. Watson Watt. These data show that for wireless bearings taken on signals averaged over the whole period of 24 hours it is extremely rare for more than 2 per cent of those bearings to be more than 20° in error; and only about 10 per cent of them are over 10° in error. Therefore, though the errors of individual observation may sometimes be 40° or 50°—and it is from such readings that direction-finding has in the past derived such a bad name—yet when the results are analysed statistically the accuracy is quite comparable with that of the instrument itself. With regard to the cathode-ray oscillograph, I think we ought to be clear that quite a big step has yet to be made before it is ready to place on board ship. To one who is used to dealing with direction-finders using frame coils with an equivalent area of 100 or 200 sq. ft., it comes as rather a shock to find that loops having an equivalent area of 20 acres are being used to obtain a readable deflection on the oscillograph! It is quite obvious that if reduction in area of the loop is to be made, the compensation can only be made by an increase in amplification. When one turns to the amplifier which is being used by the author one finds that it is dealing with voltage amplifications of the order from 5 to 200; and we do not yet

know how to produce amplifiers which give an amplification of more than about 2 000. Thus, before the system becomes a workable one in the field of navigation, considerable progress has to be made in the direction of the development of a suitable amplifier.

Major G. H. Scott: Some time ago Mr. Watson Watt came to Pulham to investigate the provision of loops for this type of direction-finder on H.M. Airship R33. It meant having loops very much smaller than those with which he had been working, and I should like to ask him whether the smaller loops have been successful in practice.

Messrs. R. A. Watson Watt and **J. F. Herd** (*in reply*): In order to avoid misunderstanding it seems desirable to amplify Dr. Simpson's statement of the provisional conclusions reached in the research on atmospherics conducted for the Radio Research Board. We would say that the available evidence indicates that all atmospherics may be accounted for by discharges of lightning character occurring in the terrestrial atmosphere; the estimated numerical distribution of lightning flashes throughout the world, the known quantities involved in typical lightning flashes, the general solar control, and the detailed study of meteorological environment of individual sources of atmospherics as located by direction-finding all favour this view.

The double orthogonal coil system of pen-recording outlined by Prof. MacGregor-Morris was proposed and adopted in principle some years ago, but it was not found economically possible to put it into practice without interfering with the progress of work regarded as more fundamental. The matter might profitably be considered again in the near future.

Prof. MacGregor-Morris counsels the substitution of "electron jet" for the traditional "cathode ray" in the description of such apparatus as that of the second paper. Habit and sentiment favour the older term, whilst reason favours a change, but not, in this instance, to a term so narrow as "electron jet." In view of the essential rôle of the heavy ions in the sensitive oscillograph which we owe to the Western Electric Co., and to Mr. J. B. Johnson and Dr. Van der Bijl in particular, the terms "ionic jet" or "ionic beam" would appear more appropriate. The latter term has in fact been used in the patent specifications (British Application No. 28971 of 1924 and related foreign applications) covering the device. We think Prof. MacGregor-Morris has given a solution as neat as any likely to be attained of the problem of combining equal deflectional sensitivities for the two plate systems with uniformity of each deflecting field.

The present position of work on fluorescent screens is that, at the request of the Radio Research Board, Sir Herbert Jackson, K.B.E., F.R.S., Director of the British Scientific Instrument Research Association, has prepared screen materials which give a more intense visual effect on brief exposures, such as those due to transient deflections, than does the usual screen material. The work is, however, still in progress; we think that the limit of screen sensitivity on short exposures to low electron velocities is far from having been reached. It is hoped that an opportunity for a report on the progress already made may present itself during the next few months. The provision of a quartz window, as mentioned by Prof. MacGregor-Morris, is certainly a useful step towards photographic recording.

The frequencies of 10 and 15 kilocycles adopted for observations on atmospherics are merely compromise values ensuring freedom from interference by signals and an adequate supply of atmospherics. It is well known that the intensity of interference by atmospherics usually increases steeply as the oscillation frequency of the receiving circuits is decreased towards the 10 to 15 kilocycle band, and there is no evidence, either in ordinary reception or in the observed wave-forms of atmospherics and our knowledge of their mode of action, that interference experienced on higher frequencies is normally absent from this lower band. Further, Mr. Shaughnessy's alarm at the appearance on one record of signals from Rugby and Leafield is sufficient confirmation of our success in the deliberate and extreme flattening of tune adopted to prevent selective preferences for atmospherics of one brand.

We feel that the answer to Prof. MacGregor-Morris's query as to sacrifice of the simplicity of the polar diagram must be an emphatic negative. He will recognize that the simplest recording of components would re-introduce the ambiguities referred to on page 614 in the second paper, but, even were this overcome, the prime consideration must be the overwhelming volume of arithmetical and statistical work so sympathetically referred to by Mr. Barfield, a volume which dictates study by limited samples from direct-reading instruments in preference to more sustained sampling by methods in which recombination of components is performed by human effort and not by the instrument.

Mr. Barfield's interesting reference to Dr. Eccles's description of the "sunrise minimum," which he reported as being particularly marked in November 1909, recalls also Round's description of a similar phenomenon at sunset [*The Marconigraph* (London), 1912, vol. 2, p. 310], and his suggestion that the timing of this minimum might serve for the determination of longitude at sea. We have never found the phenomena so well marked as in these descriptions, but the minimum N_2 of Fig. 10, is doubtless the sunset minimum in question, and is, as shown by Table 1, closely associated with the time of sunset at the receiver.

We are indebted to Squadron-Leader Johnston for a valuable discussion of the problem of navigation with and without the aid of the "wireless compass." We are sure that he will believe that we did not think the navigator's occupation gone; the problem solved by the suggested beacons was that of position-finding only, providing the successive starting points for the navigator's further work in course-setting.

We think ourselves privileged in having evoked two such lucid summaries of the problems of airways as that just referred to and the graphic summary of airship meteorology contributed by Mr. Giblett. We are strongly of opinion that the widening of the observer's horizon by the use of the instrument described will considerably reduce the total cost of providing an adequate and effective meteorological network for the great air routes.

We welcome this opportunity of expressing our appreciation of and interest in the important work being

done by M. Bureau and his colleagues in France. Whilst there appear to be important divergences between some of M. Bureau's conclusions and our own, divergences which will doubtless be cleared up by further discussion and experiment, there can be no doubt on the main point that the atmospheric is frequently a signal from the polar front, and whilst we do not regard ourselves as competent to read the text of the signal we are assured of the collaboration of Mr. Giblett, with his profound knowledge of the physics of meteorology, and of " polar front meteorology " in particular, in seeking an answer to the important question which he has now posed.

We can hardly accept the modest summary of our work made by Mr. Shaughnessy; its modesty is doubtless explained by the fact that he is a member of the Radio Research Board. Nor can we go far with him in his argument as to relations between methods and results. A discussion as to what might have been done with " any good direction-finding apparatus " might be interesting—the preliminary skirmish on this definition would certainly be so. But " has been " must always carry against " might have been," and the results quoted have only been obtained by the use of the two pieces of apparatus described, which forms strong evidence for our argument that at the best they could not *economically* have been obtained by previously existing means. Moreover, we beg Mr. Shaughnessy to refer us to any other instrument which could, in any circumstances, have disentangled the complex distribution of local sources of atmospherics shown in Fig. 4 (page 615) of the second paper. On reference to page 613 it will be found that the frequency of 10 kilocycles was that used in atmospheric observations and that the effective resistance of the circuits was very high. For the Rugby-Leafield plot to which Mr. Shaughnessy refers, the tune was set midway between their widely differing frequencies, and the damping chosen ensured that adequate E.M.F.'s could be derived simultaneously from both transmissions. We think it will be sufficiently clear from a reading of the paper that the direction-finder described possesses, in addition to its directional selectivity, all the ordinary properties of frequency selectivity, and that it is only by deliberate choice that this frequency selectivity is sacrificed in the application to atmospherics, and in the obtaining of sufficiently bad jamming to demonstrate the exceptional powers of discrimination possessed by this direction-finder. The reply to his question is thus that there is, with this direction-finder, as with ordinary direction-finders, no difficulty whatever in separating frequencies very much closer than those of Leafield and Rugby.

We thank Dr. Smith-Rose for confirmation, from his wide experience of directional observations, of the faith which is implied in our reliance on the methods described for the location of sources of atmospherics. We agree that the development work now in progress has to go further before the standard ship installation is designed, but, as the paper indicates, much smaller loops have already been used, and we have no doubt as to the early production of a mobile set. We would particularly emphasize that in none of the signal traces shown at the meeting did the voltage amplification exceed 5. Thus there is, apart from the other factors involved, a wide margin between the amplification used and that regarded by Dr. Smith-Rose as the present limit.

In reply to Major Scott, we would say that the development of an apparatus working on the much smaller loops permissible in the application to airships and other mobile stations is progressing satisfactorily, and would repeat the assurance contained in our reply to Dr. Smith-Rose.

INSTITUTION NOTES.

National Certificates and Diplomas in Electrical Engineering.

The following have been approved under the scheme drawn up by the Board of Education and the Institution :—

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Crewe Technical Institute.

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54th (East Anglian) Divisional Signals, T.A.

The Secretary is informed that there are vacancies in the above unit for commissioned officers.

Candidates for commission in the lowest rank must be between 18 and 31 years of age and of British nationality and parentage, and have had previous service in an O.T.C. and possess Certificate " A," *or* have served for 6 months in the Regular or Territorial Army, or for 3 months overseas with any military or naval Unit between August 1914 and November 1918, and be recommended by an officer under whom he has served, *or*, alternatively, must undertake to pass for Certificate " A."

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(ii) Cable, by cable wagons (horse transport) using fairly light surface cable with telegraphic apparatus and by telephone wagons, using both telegraphy and telephony.

(iii) Visual, by means of flags, heliographs and electric signalling lamps. Popham panels (for use with aircraft) are also used.

Officers need a good general knowledge of all means of communication, specializing in either (i) or (ii).

Training is carried out with the equipment held by the Unit which includes all wireless equipment, cable and telephone equipment (including commercial-type internal-combustion engines and 3 kW and 1 kW generator sets), accumulators, telegraph and telephone instruments, switchboards and Field exchanges. There is also instruction in riding, management of animals, etc. Ability to drive motor cars and motor cycles and to carry out running repairs is an advantage. Training also includes the usual drill and musketry courses, an annual camp (15 days) and, during the first two years, an initial course of 14 days (this may be done in two parts) with a Regular Army Signal Unit. Associate Members of the Institution are exempt from the initial course.

There is an oufit allowance of £40 on first commission, or, if previously commissioned, an allowance to cover renewal and repairs to outfit.

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Inquiries should be made to the Officer Commanding at the Headquarters of the Unit, Bay Lodge, The Green, Stratford, London, E. 15.

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POWER FACTOR AND TARIFF.

By EDWARD VINCENT CLARK, B.Sc., Associate Member.

(*Paper first received* 18*th May, and in final form* 24*th August*, 1925; *read before* THE INSTITUTION 4*th February, before the* NORTH-WESTERN CENTRE 2*nd February, and before the* SOUTH MIDLAND CENTRE 31*st March*, 1926.)

SUMMARY.

The great amount of attention now being given to the question of poor power factor suggests that tariffs such as are commonly used to-day are unsuitable in present circumstances. The paper contends that a wattless component of current, despite its having no energy content, involves the supply undertaking in extra running costs, and that therefore a charge should be levied for supplying it. A three-part tariff is proposed, embracing a periodic charge per kVA of maximum demand, a charge per kWh of energy, and a charge per kVA-hour of lagging wattless component. The additional running costs caused by wattless component are briefly touched on, and it is suggested that in a station with an average power factor of 0·7 the charge per kVA-hour of wattless component should be about one-ninth of the charge per kWh of energy. The question of metering the three-part tariff is discussed, and a method is shown whereby, with balanced load, a three-phase wattmeter may be "biased" to record the total energy consumption, plus or minus any desired fraction of the kVA-hours of lagging or leading wattless component.

INTRODUCTORY.

One of the troubles of many supply undertakings to-day is the low power factor of the load. Experience has shown that without constant endeavour to effect an improvement, the power factor of a system is apt to grow steadily lower as more and more small users of power are connected. The induction motor, of size appreciably greater than is necessary for the work it has to do, and running frequently at less than half load, is the chief offender in producing poor power factor. Manufacturers are able to supply motors having good power factor at all loads, and can supply various types of phase-advancing apparatus to neutralize directly or indirectly the lagging current of induction motors. The problem is therefore not a technical but an economic one; and it is from this standpoint that it must be studied.

From the point of view of an outsider, the present state of affairs presents a strange paradox. On the one hand are thousands of consumers of electricity using ordinary induction motors and perfectly satisfied with their operation, although they use a good deal more electricity for the same power than would other types of motor which are procurable. On the other hand are supply undertakings, whose business it is to supply electricity, complaining bitterly that their customers are taking more electricity than they need, and urging them, by argument and by bonus, to adopt a different type of motor or to install phase-advancing apparatus in order to reduce the quantity of electricity they consume. In what other field of supply and demand are these conditions possible? One cannot imagine, for example, a gas company imploring its satisfied consumers to adopt, for the benefit of the company and the supply generally, a type of engine which uses less gas.

The word "electricity" has been deliberately used in the preceding paragraph, to emphasize the point which lies at the root of the whole matter. A supply undertaking is essentially a supplier of electricity and not merely of power. An electric motor is essentially a piece of apparatus which absorbs electricity and delivers mechanical power. Electricity is a vague term; and for clear thinking we regard it as a matter of amperes, volts, phases and power factor; and we consider a given alternating supply as being made up of so much energy component and so much wattless component. Owing to the law of the conservation of energy, we know that a motor delivering so much brake horse-power requires a certain minimum energy component in the electricity it consumes. In accordance with its inefficiency as a converter of energy, so it requires a greater energy component in the electricity it absorbs; and in accordance with its inefficiency as a converter of electricity into energy, so it requires a wattless component in addition to the energy component.

(1) THE CASE FOR A THREE-PART TARIFF.

The Electric Lighting Acts of 1882 and 1888 and the Board of Trade Regulations made thereunder were responsible for a good many conditions which permeate the supply of electricity in Great Britain to-day; and one provision of the early Regulations was that electricity should be sold by its energy content. It was very soon found that to sell electricity at a flat rate per unit, no matter for how many hours per day it might be used, was extremely unsound from the economic standpoint. Dr. Hopkinson, in the early 'nineties, laid down the fundamental principle that the cost of supplying electricity was divisible into two items, (*a*) the running costs incurred in actually supplying the electricity required, being approximately proportionate to the units of energy consumed, and (*b*) the cost of being ready to supply, approximately proportionate to the kilowatts of the peak load; and of these two the latter was in many cases by far the greater. And Wright, with his maximum-demand indicator and method, showed how a tariff based generally on the Hopkinson principle might be made to comply with the requirements of the Regulations and receive the sanction of the Board of Trade.

The Hopkinson principle was formulated primarily for the supply of direct current, or for alternating

current used almost exclusively for lighting, where the power factor would be nearly unity, as the induction motor was not then developed. To-day the principle is very widely adopted for power supply, the charge for running costs being based on the kWh of energy consumed, and the standing charge being based on the kVA of maximum demand. By using kVA and not kW an attempt is made to charge users of current at poor power factor in accordance with the cost that their supply entails. But the fact that supply undertakings working with a tariff of this kind are not fully satisfied with their station power factor, however low it may be, is surely evidence that this tariff departs seriously from the ideal.

Extending the Hopkinson principle a stage further, one might suggest dividing to-day's cost of supplying electricity into four parts as follows :—

(*a*) The running costs involved in supplying the energy component of the electricity consumed.

(*b*) The running costs involved in supplying the wattless component of the electricity consumed.

(*c*) The standing charges incurred in being ready to supply the energy component of the maximum demand.

(*d*) The standing charges incurred in being ready to supply the wattless component of the maximum demand.

If it were possible to devise a suitable tariff based on these four items of cost, metering each item separately, and assessing the tariff under each head in such a way that any consumer must show an adequate percentage of profit on the amount of his bill, no matter how small any three of the items might be, we should have a tariff such that all customers afforded a profit to the supply undertaking, no matter what their individual power factors. And further, the lower the power factor of the general supply, the better would be the financial returns for any given demand for energy. For example, if one supply undertaking had a peak load of 10 000 kW at unity power factor and an annual sale of 20 million units, also at unity power factor, it would make adequate profits under items (*a*) and (*c*) above. A second undertaking with a peak load of 10 000 kW at 80 per cent power factor, and an annual sale of 20 million units at 70 per cent power factor, would make the same profits as the former under items (*a*) and (*c*), and in addition would make further profits on the sale of 20·4 million kVA-hours of wattless component, and on the standing charges receivable from plant capable of supplying a demand of 7 500 kVA of wattless component over and above 10 000 kW of energy component.

An ideal tariff, however, is not always a practicable one; and it seems quite impossible to frame a tariff which would differentiate adequately between standing charges on plant to supply energy and on plant to supply wattless component. To combine these two items (*c*) and (*d*) into one charge, based on kVA of peak load, though not strictly rational is undoubtedly advisable. It would appear at first sight that a customer whose maximum demand is 1 000 kVA at 70 per cent power factor entails upon the supply undertaking somewhat less standing charges, *cæteris paribus*, than a customer whose maximum demand is 1 000 kVA at unity power factor; but this is not necessarily the case, since diversity factor has material influence, and the diversity factor of wattless component is in general much lower than that of energy component.

Combining (*c*) and (*d*) into a common charge, we arrive at a three-part tariff for the supply of alternating current for power purposes as follows :—

(*a*) A charge based on the kWh of energy used.

(*b*) A charge based on the kVA-hours of wattless component used.

(*c*) A charge based on the kVA of maximum demand.

With an appropriate tariff of this nature, due regard being paid to the fact that item (*c*) is not quite ideal, the undertaking should gain by increased supply of electricity, no matter what the power factor, since energy component and wattless component would alike bring grist to the mill. The use by consumers of the simplest and most reliable form of motor—the plain induction motor rated appreciably above its normal load—would no longer be a source of annoyance to the supply undertaking, but a direct gain. Customers who preferred this type of motor would pay adequately in their bills for the expense and trouble incurred in supplying the wattless component they required. Those who desired a reduced electricity bill could secure it at the expense of increased capital cost, attendance and upkeep, if they decided that it was economical to do so, by using synchronous motors or phase-advancers. The onus of improving the power factor would be placed upon the consumer and the manufacturer's salesman, whilst the supply undertaking would be interested in the matter only to a secondary extent.

The suggestion that a low power factor should be a source of profit to a supply undertaking, rather than a disadvantage, may appear revolutionary; but it seems impossible to avoid such a conclusion, given a rational tariff. In the past, encouraged no doubt by the electric lighting Regulations, engineers have regarded wattless component as incurring too small a running cost to be worth charging for; and as long as this is supplied free of charge it naturally follows that its supply is an added expense and trouble to the undertaking. But directly it is charged for at a price, however small, which covers its cost, its supply is no longer a disadvantage, but on the contrary a direct source of profit.*

(2) The Charge for Wattless Component.

When one endeavours to ascertain the actual running cost of supplying wattless current, one encounters many difficulties. The cost is made up of a number of items, each so small as to appear practically negligible, whilst it is assuredly the case that the cost per kVA-hour of wattless component is largely dependent upon the ratio of the wattless component to the energy component demanded of the station. An undertaking with an

* An analogy may be drawn from the sale of sulphuric acid. If it were the custom, or the law of the land, that sulphuric acid, whatever its degree of dilution, should be sold at a rate based solely on its acid content, on the ground that water is of too little value to be worth considering, then it would be to the advantage of sulphuric acid manufacturers to sell acid at that degree of concentration at which it was most cheaply made. It might pay them to keep a staff of men whose main duty was to urge customers to use strong acid, and to show them how strong acid might conveniently be used in their businesses. It would certainly pay manufacturers, while still charging on acid content, to allow a discount based on the degree of concentration of the acid required. But with the realization that water, though practically valueless compared with acid, still costs something for distilling and for delivery, the manufacturer may frame a tariff based not merely on the acid content, but also on the water content of the dilute acid he is asked to supply. And with an appropriate tariff it will be more profitable to him to sell 100 tons of concentrated acid broken down to a specific gravity of 1·2 than 100 tons in the concentrated form.

average power factor of 95 per cent, for example, supplies 1 kVA-hour of wattless component for every 3 units of energy supplied; and the economy in running costs secured by supplying at unity power factor would be barely perceptible. Yet where the average power factor is about 70 per cent, so that the kVA-hours of wattless component are equal to the kWh of energy, the total running cost of the wattless component is quite appreciable, and certainly much more than three times that in the former case. And if the kVA-hours of wattless component were double the units of energy supplied, so that the average power factor was 45 per cent, the station engineer would certainly cite his power factor as a reason why his running costs could not be kept as low as those of neighbouring stations having an equal energy load at much better power factor.

The chief item comprised in the actual running cost of wattless component is the increase in I^2R loss in generators, cables and transformers. Upon a system of average power factor of 70 per cent, whose layout is such that the units spent in these I^2R losses are 10 per cent of the units generated, it is evident that a saving of 5 per cent of the units generated would be effected by abolishing all wattless current. Hence it follows that in a system such as this the running cost per kVA-hour of wattless component from this cause alone is about one-twentieth of the running cost per kWh.

A second item of loss inseparable from lagging wattless component is the extra excitation required on generators, to compensate not only for the extra drop in the system but also for the actual demagnetizing effect of such wattless component. With a station of the above nature the order of this loss would be about 1 per cent of the units generated.

Another cause of increased cost due to poor power factor lies in the increased iron, friction and windage losses in generators, etc., due to their being designed on a kVA basis. This, however, is a loss incurred in the design of the station, and may perhaps be covered by the standing charges. But a direct increase in running costs may arise from wattless component being sufficient to require an extra turbo set to be operated, with reduced station efficiency, at times when the running turbine has not yet reached its limit of capacity, owing to the overloading of the alternator. Loss from this cause should be quite trivial, except in the case of a station whose average power factor is appreciably less than that for which the station was designed, when it may be the case that the maximum efficiency of the turbine can hardly ever be attained.

Other disabilities of wattless component lie in the greater complexity necessary to maintain a satisfactory pressure on the distribution system, since wattless component as a rule causes a larger drop than an equal current in phase, and in the increased difficulty it causes in effectively tying two distant stations; whilst the use of reactances to prevent disturbances in one part of a system from affecting other parts would be feasible to a much greater extent if wattless component were absent. In general, these disabilities have to be met by increased capital expenditure, and therefore cause increased standing charges rather than increased running costs. It is quite certain, however, that under heads such as these, supply undertakings are caused to incur running costs which could be avoided if wattless component were absent; and that even though such costs are not directly influenced by the actual demand for wattless component they are indirectly increased as the general power factor of the system falls. And if, on a three-part tariff, standing charges are levied on the kVA of peak load irrespective of power factor, it is desirable that extra expense due essentially to wattless component should be regarded as running costs rather than as standing charges, whenever any doubt occurs as to their allocation.

No doubt a station engineer, with a full knowledge of the system of supply and having available the station log sheets for the past, could compute approximately what saving in running costs he could have effected in the past year had there been no wattless component to supply, and hence could deduce the approximate running cost per kVA-hour of the wattless component supplied. Undoubtedly the ratio of the running cost per kVA-hour of wattless component to cost per kWh of energy would differ markedly in different stations, increasing steadily as the power factor fell. But seeing that in a station with an average power factor of 70 per cent and an I^2R loss of 10 per cent of the units generated, a saving of 5 per cent of the units generated would be effected in I^2R loss alone by abolishing wattless component, the author would suggest that for such a system a reasonable assumption is that the total running cost per kVA-hour of wattless component is in the neighbourhood of 10 per cent of the amount normally regarded as the running cost per kWh.

In other words, if this assumption is correct, an undertaking with a system of the above nature which at present operates on a two-part tariff of £Z per annum of kVA peak load, plus $10Y$ pence per kWh of energy supplied, might appropriately adopt a three-part tariff of £Z per kVA of peak load, plus $9Y$ pence per kWh of energy, plus Y pence per kVA-hour of wattless component. Or, more specifically, a two-part tariff of £5 per kVA demand plus 0·5d. per kWh might be replaced by a tariff of £5 per kVA demand plus 0·45d. per kWh, plus 0·05d. per kVA-hour of wattless component.

Naturally, such a tariff might include any of the ordinary provisions for discount according to quantity, and sliding scale in accordance with price of coal, etc.

Assuming for the sake of argument that this ratio of 9 : 1 is correct for the cost per kWh of energy component and per kVA-hour of wattless component in the case of the station above cited with 70 per cent load factor, it follows that the cost per kVA-hour of wattless component will be proportionately much less in the case of a similar station of 95 per cent power factor, and proportionately much greater in the case of a station having an average power factor of 55 per cent. And this leads to an important difference between the assessment of the charge per kVA-hour on a three-part tariff and the charge per kWh on a two-part tariff. In the latter case we know that increased sales mean, in general, reduced costs of generation—that an extra 10 per cent in units generated will not increase the generating costs by 10 per cent—and conversely that a 10 per cent decrease in units generated will not result in a 10 per cent

decrease in generating costs. Consequently, it pays to assess the running costs per unit on a low basis, including all doubtful items in the standing charges, in order to encourage the use of as great a number of units as possible. With wattless component, however, the opposite is the case. Additional kVA-hours of wattless component, unless accompanied by a corresponding increase in the kWh required, involve greater running costs than the average cost per kVA-hour; and therefore the tariff per kVA-hour of wattless component should be on the high side, tending to discourage rather than encourage an undue demand for wattless component. Thus it follows that in assessing the running cost of wattless component, an undertaking may with advantage assume an average power factor somewhat worse than that actually existing.

A further point arising from this is that with a three-part tariff it should in general be profitable to a supply undertaking to allow for leading wattless component a bonus equal to the rate charged for lagging. This would not be the case if there were any possibility of the power factor of the system being thereby raised to unity or anything approaching such a figure, as in that case the profit accruing to the undertaking from the supply of wattless component to one consumer would be handed back to another. But seeing that the most one can expect in the way of improvement in power factor from this cause is a matter of a few per cent only, one may regard leading wattless component as having an intrinsic value to the undertaking equal to the cost of the most expensive kVA-hours of lagging component, and therefore as fully justifying a bonus assessed at a rate showing some profit on the average cost. This applies, of course, only to leading component taken at time of load. Leading component taken by static condensers during the slack hours is on quite a different footing.

It is often suggested that as it is poor power factor that is of serious import, whilst with a good power factor of, say, 90 per cent the wattless component adds very little to the running costs, it is rational to levy no extra charge for out-of-phase current upon those customers whose power factor is above a named figure, merely surcharging in some way those whose power factor is decidedly bad. This course, however, appears to be both illogical and impolitic. It is the power factor of the station as a whole which determines the running cost of the wattless component; and a particular customer's individual power factor has little bearing on this cost, save as regards losses in that part of the system —transformers and service lines—of which he is almost the sole user. Given two neighbouring consumers having identical power loads, except that one has a power factor of 0·7 and the other of 0·89—that is to say, each taking the same kWh per annum, but the one taking twice as many kVA-hours of wattless component as the other—there is identical benefit to the supply authority, as far as running costs are concerned, if the latter consumer improves his power factor to unity as if the former improves his to 0·89; and tariffs should be such as to encourage the one improvement as much as the other. Further, it is quite probable that a power consumer whose average power factor is 0·89 has already installed some phase-advancing apparatus, and by a little care might readily improve his power factor still more if offered suitable inducement; whereas the consumer whose power factor averages 70 per cent probably operates nothing but induction motors, and could not effect much improvement except at considerable cost.*

(3) Metering under a Three-Part Tariff.

A lesson learnt in the early days of electric lighting is that any form of charging for electricity which is confusing to the lay mind is intrinsically bad from the psychological standpoint. If a consumer can read his meters and compute his electricity bill he is usually satisfied, the only dubitable point being the accuracy of the meter. If, on the other hand, he cannot read his meters, or cannot follow the manner in which his bill is computed from them, he is prone to consider that the supply undertaking may be defrauding him, and that any increase in his bill over the previous amount is probably unjustified. On these grounds most undertakings which adopted the maximum-demand tariff for lighting supply found it expedient to offer as an alternative a flat rate; and this was preferred by most customers. Many forms of tariff based on power factor suffer from the defect that the meter readings are not directly converted into terms of money. But the three-part tariff suffers from no undue trouble on this score, nor in most cases from difficulty in metering.

For measuring a single-phase supply on the three-part tariff one would require three meters, viz. a maximum-demand kVA meter, an ordinary watt-hour meter, and a sine meter, i.e. an ordinary watt-hour meter modified by introducing a time-lag of 90 degrees into the current or voltage. For three-phase work, similar meters of a three-phase type might be suggested, but in most cases a simpler form of metering may be used. The kVA-hours of wattless component will never exceed twice the kWh of energy consumed by any normal power user, and will rarely exceed it by 50 per cent; whilst the rate charged will be of the order of one-tenth. It follows that an error of 5 per cent in the measurement of kVA-hours is of less importance than an error of 1 per cent in the measurement of kWh. Consequently, in the majority of cases it will be quite sufficient to assume that the three-phase load is balanced, as far as the measurement of wattless component is concerned; and with this assumption the sine meter need be nothing more than a simple single-phase watt-hour meter, the series coil being connected in one main and the pressure coil between the other two, the reading of such a meter on a balanced load giving $1/\sqrt{3}$ of the total kVA-hours of wattless lagging component taken, with a negative reading if the current is leading. With such a meter the dial might be marked to read $\sqrt{3}$ times the actual

* The case cited illustrates incidentally one of the anomalies caused by assessing standing charges upon the kVA of maximum demand. If these two consumers have simultaneous peak loads, each of 100 kW, but one at 0·70 power factor and the other at 0·89, their standing charges at £5 per kVA per annum will be £715 and £562 10s. respectively, whilst their joint peak load will be 200 kW at about 0·8 power factor. If either consumer should now install condensers taking 50 kVA leading current at zero power factor, the joint peak on the station due to the two will be 200 kW at 0·89 power factor, i.e. the technical benefit to the supply undertaking will be identical. Yet the financial benefit of the installation of condensers to the consumer will be only £62 10s. per annum if installed by the second, but £152 10s. per annum if installed by the first.

consumption, so as to record the wattless kVA-hours of the three phases; or, alternatively, it might be marked to read "equivalent units," so that the wattless component recorded might be charged for at the same rate as the units of energy.

The explanation of the use of the third meter should not involve any great confusion to non-technical consumers. Most power users probably have sufficient knowledge of the direct-current motor to understand that, in addition to the operating current through the armature, one must have magnetizing current through the field. Similarly, the induction motor requires both operating or energy current to convert into power, and magnetizing current to create the field, though in this case both currents flow through the same wires. The meters are so designed that the one records the consumption of energy current, and the other the consumption of magnetizing current. This explanation does not depart very far from strict accuracy, and is probably much more comprehensible than any explanation involving the term "power factor." Further, it at once assists the consumer to understand the disadvantage of using a motor much larger than is necessary for the work it has to do. Naturally the larger motor will require more magnetization than a small one.

The sine meter, whether three-phase or single-phase, suffers from the fact that it reverses with leading current. If it is allowed to reverse, it gives full credit for leading current taken by condensers left in circuit all night. If provided with a pawl to prevent reversing, it fails to give credit for leading current taken at the time of load. To combine the sine meter with the watt-hour meter, by providing the several armatures upon the one spindle, the sine-meter portion being appropriately weaker than the other part, would overcome this difficulty, as in this case a non-return pawl would be reasonably satisfactory; but it would involve an entirely new departure in meter manufacture.

However, there are other ways of overcoming this defect, in the case of balanced loads, without introducing additional complications or requiring special meters, since two ordinary single-phase meters, their series coils being connected in two of the mains and their pressure coils thence to the third main, measure by the sum of their readings the total energy consumption, irrespective of any want of balance, while the difference between their readings gives the kVA-hours of wattless component, assuming balanced load, from the well-known fact that the lagging wattless kVA-hours equal $\sqrt{3}(W_1 - W_2)$, or leading wattless kVA-hours equal $\sqrt{3}(W_2 - W_1)$, where W_1 and W_2 are the respective readings of the two meters.

The use of two such meters involves a little difficulty in computing the power bill from the meter readings, but not a great deal if the tariff is suitably quoted. Three methods may readily be devised, all of which enable the consumer to compute his power bill from his meters without undue complication.

Method A.—The tariff charges f_1 pence per unit for all units recorded on No. 1 meter, and f_2 pence per unit for all units recorded on No. 2 meter. (If x pence is the price per unit for energy component, and y pence is the price per kVA-hour of wattless component, then $f_1 = x + \sqrt{3}y$ and $f_2 = x - \sqrt{3}y$.)

Method B.—The tariff charges f_0 pence per unit for all units recorded, plus or minus f_3 pence per unit of the difference between the meter readings, according to which is the greater. (Hence $f_0 = x$, and $f_3 = \sqrt{3}y$.)

Method C.—The tariff charges f_1 pence per unit for all units recorded, less a rebate of f_4 pence per unit for all units recorded on meter No. 2. (In this case $f_1 = x + \sqrt{3}y$, and $f_4 = 2\sqrt{3}y$.)

Of these three methods, the last would probably prove the most satisfactory. It makes use of the psychological fact that a high price less a rebate is in general preferred to a low price plus a surcharge, even though the actual cost is the same, whilst it offers an explanation of the form of tariff which would probably be fairly satisfactory to the lay mind. The explanation is as follows:—

Motors badly designed or ill suited to their work may take so much magnetizing current as to draw double the requisite current from the line. The tariff is based on such motors, and the meters are so designed that with such a motor the entire power consumption is recorded on No. 1 meter, and No. 2 remains idle. With motors of better design, or more appropriately used, the magnetizing current is smaller and the cost of supply in consequence is less, so that the consumer deserves a rebate. Whatever the magnetizing current, the two meters jointly record the total power consumption, whilst the reading of No. 2 meter is directly proportionate to the saving in magnetizing current, and is therefore a measure of the amount of the rebate.

An explanation of a similar nature, but involving power factor instead of magnetizing current, may readily be devised, if preferred. Naturally, the consumer must take his meters on trust—just as he must with any gas, water or electricity meter—but the explanation appears to account fully for the use of the two meters, and for the method of computing the power bill.*

With two such meters, consumers get full benefit for leading power factor at the time of load, whilst the provision of a non-return pawl on No. 1 meter ensures that the consumer's rebate for leading current extends only down to a power factor of 0·5. With a lower leading power factor than this he will pay at an increasing rate; and it will therefore be to his interest to switch off static condensers when his works are at rest.

(4) The Biased Meter.

However, if the units of energy do not constitute a rational basis for the electricity bill, it seems quite unnecessary to measure them, if one can provide a meter that will directly measure something else which gives a truer basis for computing the charge. The average consumer's knowledge of electricity is very vague, and he probably has little idea of what constitutes the "Board of Trade unit" which his meter records and with which his bill charges him. If his meter records in "virtual units," and his bill is computed directly from the meter readings, charging

* The use of two single-phase meters would undoubtedly lead to confusion if one showed a negative reading. This will be the case if the average power factor is less than 0·5. But such conditions should very seldom be met, as this power factor corresponds to that of an induction motor at about one-fifth full load.

him at a flat rate per virtual unit (with or without the standing charge per kVA of maximum demand), he is likely to be quite as content to accept his bill as if it charged him a flat rate for Board of Trade units. And, by a very slight modification, a standard type of three-phase watt-hour meter is readily adapted to record, upon a balanced load, not the kWh of energy consumed alone, but the kWh of energy plus or minus any desired fraction of the kVA-hours of lagging or leading wattless component consumed. That is to say, one may adopt a three-part tariff of the type suggested, using for those consumers whose load is reasonably balanced the same instruments as are necessary to-day with a two-part tariff, namely a maximum-demand kVA meter, and an ordinary three-phase watt-hour meter, the latter being "biased" to read not in Board of Trade units but in virtual units to be charged for at a flat rate in accordance with the requirements of the proposed three-part tariff.

The three-phase meter needs only a very slight alteration. It must be of the type comprising two single-phase armatures upon a common spindle, and recording upon a common dial in the usual manner. The only modification necessary is to arrange that when one element is tested on single-phase current, the meter shall run a certain percentage fast, and that when the other element is similarly tested the meter shall run an equal percentage slow. If the elements run respectively x per cent fast and slow, we have a meter which, appropriately connected to a three-phase balanced load, measures accurately the kWh of energy consumed plus $x/(100\sqrt{3})$ times the kVA-hours of lagging wattless component, minus $x/(100\sqrt{3})$ times the kVA-hours of leading wattless component. If, as suggested above, lagging wattless component is computed to cost (per kVA-hour) one-ninth as much as each kWh of energy, then $x = 19{\cdot}2$ (that is, the two elements of the meter are adjusted to run respectively 19·2 per cent fast and slow) and by charging at 0·45d. for all virtual units recorded, we are actually charging at 0·45d. per unit of energy plus 0·05d. per kVA-hour of lagging wattless component, less 0·05d. per kVA-hour of any leading wattless component.*

The requisite bias may be given to a three-phase meter in various ways: (1) By designing the armatures or fields to have different strengths; (2) by having different ballast resistances in their shunt circuits; (3) or where current or pressure transformers are used, by having a different number of turns in the secondaries. Existing meters could probably be given the appropriate bias by so adjusting the brake as to make the meter run the required degree fast, and then inserting a suitable extra ballast resistance in the one shunt circuit.

If the consumer's load were not strictly balanced on the three phases, the biased meter would give a somewhat erroneous reading; but with any want of balance due to slightly unsymmetrical design of induction motors, or to similar cause, the error should be quite negligible. Lighting is perhaps the chief source of want of balance, but in many cases this will be taken at a lower pressure and be metered separately. Where the load is known to be unbalanced, e.g. where some single-phase apparatus is used, then by connecting that apparatus appropriately it could be ensured that the single-phase load is charged at slightly above normal rates. The amount of this surcharge will not be great; and one is justified in making a somewhat higher charge for single-phase supply taken from three-phase mains.*

With the biased meter, a non-return pawl is desirable to prevent the reversal of the meter under the effect of static condensers. A meter biased to rate wattless component at one-ninth the cost of energy would reverse with a leading power factor of about 11 per cent. A non-return pawl means that energy with a lower leading power factor than this is obtained free of cost, and condensers may be left in circuit all night with neither bonus nor charge to the consumer. Probably where condensers are installed by a consumer it is to the interest of the supply undertaking that they should be left in circuit continuously, even though the benefit accruing is not sufficient to warrant an actual rebate other than at time of load.

Naturally, in connecting a biased meter in circuit it must be put in the proper phase sequence, or it will give a bonus for lagging current instead of for leading current. This should, however, involve very little trouble in installing the meter, if the terminals are properly marked. The simplest positive test would perhaps be to place a single-phase test-coil of high inductance across the load terminals coming from the two series coils, when the meter should at once revolve if properly connected.

* This is readily established as follows:

If I is the current per phase, V the voltage (in kilovolts) between phases, and ϕ the angle of lag, then the power in the circuit at any time is $\sqrt{3}VI\cos\phi$ kilowatts, and the wattless component is $\sqrt{3}VI\sin\phi$. The energy consumed in any period Σh is $\Sigma\sqrt{3}VIh\cos\phi$ kilowatt-hours, and the kVA-hours of wattless component are $\Sigma\sqrt{3}VIh\sin\phi$.

The one armature alone should register $\Sigma VIh\cos(\phi - 30)$, but, being x per cent fast, it actually records $(1 + 0{\cdot}01x)\Sigma VIh\cos(\phi - 30)$.

The other armature alone should register $\Sigma VIh\cos(\phi + 30)$, but, being x per cent slow, it actually records $(1 - 0{\cdot}01x)\Sigma VIh\cos(\phi + 30)$.

The meter as a whole therefore records

$$
\begin{aligned}
&(1 + 0{\cdot}01x)\Sigma VIh\cos(\phi - 30) + (1 - 0{\cdot}01x)\Sigma VIh\cos(\phi + 30)\\
&= \Sigma VIh\cos(\phi - 30) + \Sigma VIh\cos(\phi + 30)\\
&\qquad + 0{\cdot}01x[\Sigma VIh\cos(\phi - 30) - \Sigma VIh\cos(\phi + 30)]\\
&= \Sigma 2VIh\,.\,\tfrac{1}{2}\sqrt{3}\cos\phi + 0{\cdot}01x\Sigma 2VIh\,.\,\tfrac{1}{2}\sin\phi\\
&= \Sigma\sqrt{3}VIh\cos\phi + \frac{x}{100\sqrt{3}}\Sigma\sqrt{3}VIh\sin\phi
\end{aligned}
$$

i.e. kilowatt-hours of energy, plus $x/(100\sqrt{3})$ times kilovolt-ampere-hours of wattless component.

If ϕ is negative, i.e. if the current is leading, clearly the second term has a negative sign.

* If a three-phase load be unbalanced, but the voltage triangle be not distorted, the nature of the error introduced by the use of the biased meter can readily be seen from the fact that any out-of-balance load may be regarded as the superposition on a balanced three-phase load of one or two single-phase loads between wires. Assume the phase sequence of rotation to be A, B, C, and the series coils of the meter to be in lines A and C. Then No. 1 armature, biased to run fast, is in line C, and the other in line A. Single-phase current taken between lines A and B is metered by No. 2 armature alone, and its wattless component is ignored. Thus single-phase load between these lines is charged for at a discount of x per cent below normal energy rate, and no charge is made for its wattless component. Similarly, single-phase current taken between lines B and C is charged for with a surcharge of x per cent above normal energy rates, again no charge being made for wattless component. Single-phase current taken between lines A and C can readily be seen to be charged for at normal rates for energy, whilst its wattless component is charged for at three times the normal wattless rate. Thus in the normal case, where the out-of-balance load is lagging, there is an undercharge if the single-phase load is connected between lines A and B, and an overcharge if between lines B and C, or A and C. Further, if the load is between mains A and C, the surcharge is zero at unity power factor, increasing as the power factor falls; whilst if the load is between mains B and C the surcharge is a maximum at unity power factor, falling to zero at 0·5 power factor. In any ordinary case the error will be trivial. For example, with power factor 0·8, and out-of-balance 10 per cent of the total load, the error in the charge for running costs will be approximately 1½ per cent if the out-of-balance is caused by load between lines A and C, 1 per cent if between lines B and C, and 2½ per cent if between lines A and B, on a system where the wattless component is assessed at one-ninth the cost of the energy component.

No doubt the sanction of the Electricity Commissioners would be required before biased three-phase meters would be allowed, in the case of many British supply undertakings. They do not record in units of energy consumed, nor is it possible to deduce from their readings what has been the actual energy consumption; and therefore they do not comply with the requirements of the Electric Lighting Acts. Nevertheless, they measure the consumption of electricity on a balanced three-phase load on a perfectly definite basis; and their accuracy can readily be tested by testing each single-phase element separately. There appears therefore to be no valid reason why approval should not be given to this type of meter in accordance with the provisions of the Electricity (Supply) Act, 1922.*

Where a supply undertaking is seriously perturbed by the poorness of its normal power factor, the use of the biased meter for the small consumer using induction motors seems to offer great advantages. The determined charge for wattless component, however small, can be introduced with no expense save the initial one of altering the watt-hour meter installed. The consumer is not troubled by the addition of an extra meter that he does not understand, nor are his bills made up in any different form from that he is accustomed to, save that he is now assessed in "virtual" units instead of in "Board of Trade" units. Any misgivings that he may have on that score will be largely alleviated by the fact that while the number of virtual units recorded is not markedly greater than the Board of Trade units recorded hitherto, the price charged for them is some 10 per cent less. With an appropriate charge, the returns obtained by the undertaking from the sale of wattless component should reconcile it to a low power factor; and only a serious drop in the average power factor would necessitate an alteration in the ratio of the respective charges for wattless component and for energy. Clearly it is only an alteration in this ratio which requires an alteration in the bias of the meters. Indeed, for all power customers, large or small, except where the load is seriously out of balance, the biased meter should be quite satisfactory to the supply undertaking; though a power user who installs a synchronous motor or other mechanical phase-advancing apparatus might prefer two single-phase meters or unbiased three-phase meter plus sine meter, in order that he might more clearly see if he was using his phase-advancer to the best advantage. Apart from the Electricity Commissioners' Regulations, there is no reason why an undertaking deciding to adopt a three-part tariff should not use a biased meter plus a kVA maximum-demand indicator as standard equipment, giving consumers who required it the option of having three meters, on the payment of extra meter rent; and requiring consumers having single-phase apparatus to connect it to a special circuit which should either be separately metered or else be taken direct from the appropriate terminals of the biased meter.

* A particular field in which the biased meter should prove useful is that of metering the supply transmitted by a tie line connecting generating stations belonging to undertakings that have no financial connection with one another. The ensuing decade will certainly see in England a great extension of tie lines between power stations, both large and small; and one may anticipate that the economic problems concerning the basis of payments for the supply transmitted through such lines will be considerably more intricate than the technical problems involved in their provision. The importance of the power factor of the supply furnished by one undertaking to another, and the technical difficulties involved in delivering power at a specified lagging power factor, are such that it appears essential for any tariff to pay considerable regard to this matter, since a charge which ignored power factor of the load transmitted would tend to cause endless disputes between the engineers operating the various stations connected to the tie line. A composite tariff embracing a charge per kWh of energy, plus a charge per kVA-hour of lagging wattless component, with the latter charge set at such a figure that each station preferred to carry as much of its own lagging current as it could adequately handle, would have a great deal in its favour. The biased meter, without the non-reversing pawl, should afford a very simple means of metering such a composite tariff.

Conclusion.

In conclusion the author submits that, although it has no energy content, wattless component of electricity supplied to consumers has a real value to them, and in many cases entails a real running cost to the undertaking; that where low power factor is seriously perturbing a supply undertaking, a rational tariff should include a charge for wattless component, and that a charge based on the kVA-hours of lagging wattless component consumed, with an equal rebate for leading wattless component taken at time of load, is a reasonable basis for such charge, although not absolutely ideal; and finally, that the adoption of a tariff embodying such a charge may be arranged without undue complication of metering methods, and without entailing perplexity in the minds of non-technical users of power.

Schedule.

The following table shows the annual power bill under a three-part tariff of £5 per annum per kVA of maximum demand, plus 0·45d. per kWh of energy, plus or minus 0·05d. per kVA-hour of lagging or leading wattless component, for five consumers having the same

Table.

Consumer	Peak load	Cost at £5 per kVA	Energy	Cost at 0·45d. per kWh	Wattless component	Cost at 0·05d. per kVA-hour	Total cost
	kVA	£	kWh	£	kVA-hours	£	£
A	1 150	5 750	1 440 000	2 700	1 440 000	300	8 750
B	1 150	5 750	1 440 000	2 700	1 080 000	225	8 675
C	1 000	5 000	1 440 000	2 700	nil	nil	7 700
D	1 000	5 000	1 440 000	2 700	480 000	100	7 800
E	1 000	5 000	1 440 000	2 700	{480 000 leading	{100 (Cr)	7 600

peak load of 1 000 kW, and the same annual consumption of 1 440 000 Board of Trade units.

"A" has induction motors with a peak load of 1 000 kW at 0·87 power factor (1 150 kVA), and average power factor of 0·707.

"B" is the same consumer, but with motors rearranged to give an average power factor of 0·80.

"C" has synchronous motors operating at unity power factor at all times.

"D" is the same consumer, paying little attention to excitation save at peak load, and having an average power factor of 0·95 lagging.

"E" is the same consumer, with excitation carefully controlled and having an average power factor of 0·95 leading.*

[The discussion on this paper will be found on page 640.]

* It may be well to point out that where a consumer has synchronous motors capable of giving a leading power factor at peak load, it is wrong on either a two-part or a three-part tariff to base his standing charge on kVA of maximum demand, as he is then penalized for leading power factor at peak load.

THE IMPROVEMENT OF POWER FACTOR.

By Edgar Wall Dorey, Associate Member.

(*Paper first received 17th November, and in final form 29th December,* 1925; *read before* The Institution *4th February, before the* North-Western Centre *2nd February, and before the* South Midland Centre *31st March,* 1926.)

Summary.

The first part of the paper summarizes the principal types of apparatus employed for the improvement of power factor, and gives a description of the modern static condenser and also of types of power-factor-rectifying plant that have been developed during the past three years.

The second part of the paper outlines various forms of power-factor tariff in force in Great Britain, and is divided into two main classes; first, those based on kVA demand, and second, those incorporating a power-factor bonus or penalty on the total supply bill.

Systems of metering employed in conjunction with power-factor tariffs are briefly dealt with.

Modern Methods of Improving the Power Factor.

In a paper written by the late Dr. Gisbert Kapp and read before the Institution on the 16th November, 1922,* various kinds of plant in use at that time for the improvement of power factor were described.

Auto-synchronous and synchronous motors.—It is unnecessary to enlarge further on what has already been written in regard to the use of auto-synchronous and synchronous motors, as, since the date of Dr. Kapp's paper, there has been no appreciable alteration or addition to the types then described.

Rotary condensers.—The rotary condenser still finds little favour in Great Britain, where its field of application is very limited. The rotary condenser has a comparatively high loss, which is usually not less than 5 and may be as much as 7 per cent, and when this loss is capitalized, the rotary condenser, under the conditions ruling in Great Britain where power is mainly generated from coal, compares very unfavourably with other forms of power-factor-improving apparatus such as static condensers. Whilst in the larger sizes, say 500 kVA and upwards, the rotary condenser is, when compared with, say, the static condenser, less expensive in first cost, it is much less economical and more costly when running costs are taken into consideration.

To take as an example a 1 000 kVA condenser equipment, the difference in losses between static condensers and rotary condensers would be of the order of at least 4 per cent. With a 12-hour working day, 300 days per annum, this would be the equivalent of 144 000 units lost, and at 1d. per unit sold this is approximately £600 per annum. If this difference be capitalized it will show the static condenser installation to be by far the more economical.

* *Journal I.E.E.*, 1923, vol. 61 p. 89.

Ball and Roller Bearings for Induction Motors.

The adoption of power-factor tariffs by supply undertakings has compelled designers to produce an induction motor with a very high inherent power factor, and the introduction by many manufacturers of a.c. motors fitted with ball and roller bearings has assisted greatly to this end. The smaller the air-gap the higher is the power factor, and it is obvious that with ball and roller bearings, where the wear that is attendant upon the use of the journal bearing has not to be contended with, it is possible to use a much smaller air-gap, which is a feature of modern design.

An improvement of 2 or 3 per cent in the power factor represents quite an appreciable saving on the supply bill where a power-factor tariff is adopted, and it would appear that ball and roller bearings will play an important part in the design of a.c. induction motors in the future, and many of the leading British makers to-day adopt such bearings as standard.

Static Condensers.

The oil-immersed electrostatic condenser was briefly described in Dr. Kapp's paper, but it is now proposed to deal more fully with this type of apparatus used for power-factor improvement.

Condensers of this type are manufactured in Great Britain principally by Messrs. British Insulated and Helsby Cables, Ltd., of Helsby, and the Telegraph Condenser Co., Ltd., of London. The condensers consist primarily of so-called Mansbridge plates, these comprising a length of paper coated with tin under the Mansbridge process. In the construction of condensers the Mansbridge plates are separated by the requisite thicknesses of paper used as the dielectric, the number of thicknesses being dependent upon the voltage applied across the terminals of the condenser unit. Generally speaking, each unit of the condenser has a capacity of approximately 1 microfarad, but this may be greater or less according to the special conditions obtaining on the circuit.

Take as an example a 100-kVA 600-volt 50-cycle three-phase condenser; this would have a capacity of 885 μF and there would be approximately 295 separate units connected in parallel on each phase, the phases themselves being connected in delta.

The two principal makers of condensers referred to above assemble the units in frames, the frames being fixed into boiler-plate tanks and completely oil-filled. The modern oil-immersed static condenser, which is now the result of many years' experience in the con-

struction and application of this type of plant, may be regarded as a very reliable and efficient apparatus for the improvement of power factor.

A good deal has been said about the risk of resonance due to the connection of static condensers, but it will be agreed that experience is the best guide, and it may be safely said that over many years no difficulty whatever has been experienced in the application of condensers due to resonance. It is not claimed that resonance may not occur under certain exceptional conditions, but under the ordinary industrial conditions prevailing not only in Great Britain, but overseas, experience goes to show that resonance does not occur.

The static condenser, as built in Great Britain, is essentially a medium-pressure apparatus, the most economical voltage being about 600, but condensers have been, and are, built for direct connection to supplies up to 3 300 volts. It should be noted that only in exceptional cases is it cheaper to supply a high-tension condenser, and that the saving is not even then very material, usually not more than 10 to 15 per cent of the overall cost of the equipment.

Undoubtedly the right place to put the condenser is on the low-tension circuit, as by so doing the improvement will be effected as far as possible out on the distribution network, and it has been found in practice that the call for high-tension condensers is very small compared with that for low-tension ones.

A case has been reported from overseas of a British-made 100-kVA 3 300-volt outdoor condenser which, for the purpose of test and experience generally, is connected direct across the high-tension overhead transmission line without any protection whatever, and is therefore subject to every kick and surge on the system. Nearly 12 months have now elapsed since the condenser was first connected and it continues to give every satisfaction. This should be sufficient evidence to show that the static condenser does not in reality possess the attributes of frailty so frequently ascribed to it.

A comparatively new development is the low-tension pole-type condenser connected direct across pole-type step-down transformers, this application being particularly useful in the case of rural distribution. A number of British-made condensers of this type have been working for some considerable time in New Zealand, and it is reported by the engineer of one Power Board that, from the point of view of improved regulation only, the installation was worth while. In this case, however, the annual saving effected is sufficient to repay about 70 per cent of the cost of the equipment, and to this has to be added the increase in the useful output of the transformer, as the condenser being connected on the low-tension side of the step-down transformer unloads the transformer of wattless current, and for every 2 kVA of condenser capacity under industrial conditions the load on the transformer will be reduced by approximately 1 kVA.

The efficiency of the static condenser is very high, about 99·7 per cent, so that the losses are almost negligible. A bank of direct-connected condensers having an output of 1 000 kVA would have a loss of only 3 kW. Where auto-transformers are used for stepping up the voltage from that of the supply to the most economical voltage for the condenser, the auto-transformer losses have to be added, but the overall losses of large complete equipments for the usual industrial voltages may be taken to be between 1 and 1·5 per cent of the output in kilovolt-amperes.

It is well known that the output of a condenser is directly proportional to the plate area, and inversely proportional to the thickness of the dielectric, which latter is mainly dependent upon the applied voltage across the plates.

In the construction of paper condensers two or more thicknesses of paper are used according to the voltage applied, and it will be obvious that for each definite number of papers there is a maximum safe working voltage, and to obtain the most economical results it is desirable to work as closely as possible to this maximum safe voltage.

The microfarad capacity of a condenser is worked out from the following formula:—

$$\text{Microfarads} = \frac{(\text{kVA}) \times 10^9}{2\pi f V^2}$$

where kVA = output of condenser,
V = voltage applied across condenser plates,
f = frequency of the supply.

Taking a 100-kVA condenser on a 50-cycle supply, the capacity would be:

at 600 volts, 885 μF
and at 440 volts, 1 650 μF

With the two principal makes of condenser referred to in the foregoing the type of unit used in either case would be the same, therefore at 440 volts the condenser would require to be 86 per cent larger and approximately 80 per cent more costly than at 600 volts. To overcome this it is usual in condenser practice to step up the voltage by means of an auto-transformer to the most economical voltage for the condenser—in the above case, 440 to 600 volts. The auto-transformer is comparatively inexpensive and the overall reduction in price for the complete equipment very considerable.

A high-tension 3 000-volt condenser would comprise the requisite number of low-tension condenser units connected in series inside the tank to give the maximum working voltage across each unit. Each unit of the condenser, therefore, would be working at or near its normal designed voltage, and the number of such units would be the same as for a low-tension condenser of the same voltage as that applied across each unit. For example, 5 units in series each working at 600 volts would give the required result for 3 000-volt working; the actual number of 1-μF units used in the condenser would be the same as for 600-volt working, hence the cost would be approximately the same. It is for this reason that a high-tension condenser is usually not less, but more, costly than a low-tension condenser of the same output, and the use of high-tension condensers is not encouraged.

The connections of a standard auto-connected condenser equipment are shown in Fig. 1.

It will be seen that the condenser is connected direct to the auto-transformer, and the windings of the latter therefore provide a path for discharging the condenser on switching out or on failure of supply. If a condenser is connected direct across the supply mains some form

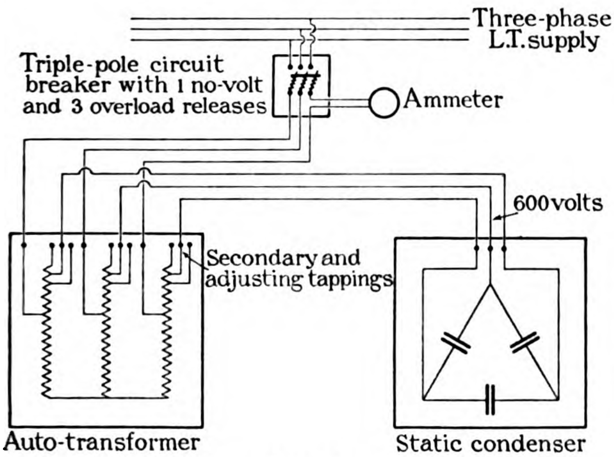

FIG. 1.

of discharge circuit is necessary, and this takes the form either of resistances permanently connected across the condenser terminals inside the tank, or of resistances so arranged inside the circuit breaker as to discharge the condenser on switching out.

course be of sufficient copper section to carry only the condenser current.

The transformer provided with an overwinding across which a condenser is connected works in parallel with other transformers, and this will result in the condenser capacity being split up over the whole bank of transformers instead of being confined to the over-wound transformer only. This point is important, as should it be necessary to add to, say, two 500-kVA transformers working in parallel in a substation a further 500-kVA transformer and, say, a 300-kVA condenser, then the new 500-kVA transformer could be overwound for the condenser, involving no alteration to the existing transformers. Fig. 2 shows the loading and phase angle of the various circuits of an overwound-connected condenser equipment.

The majority of supply undertakings in Great Britain, particularly those supplying large industrial areas, have connected to the system during no-load and light-load hours a very large transformer capacity drawing excitation current from the mains. So serious is this in many cases that some supply undertakings, such as the Clyde Valley Electrical Power Co., give in effect a substantial bonus to those consumers who keep static condensers or other power-factor rectifiers on the system during no-load hours.

Where a supply undertaking is faced with bad voltage regulation and low power factor, whether or not a power-factor tariff is in force, it should be possible to improve matters considerably by connecting direct across the

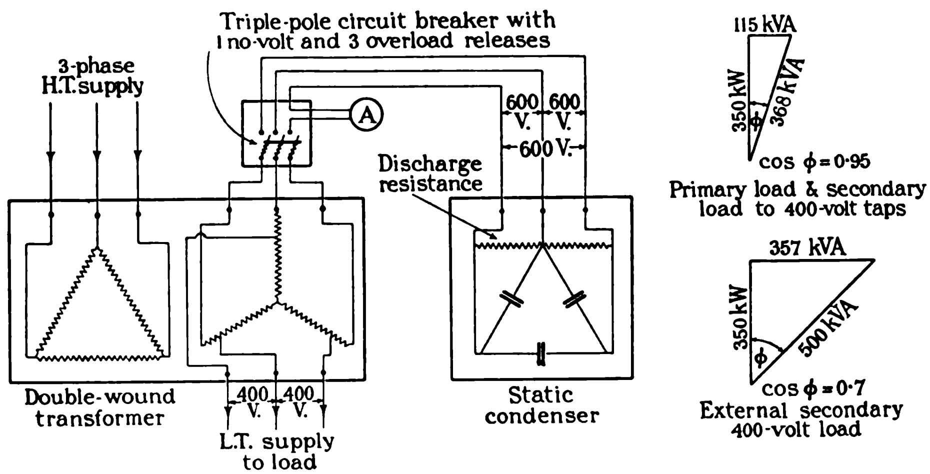

FIG. 2.

Load on primary = 368 kVA (resultant of two secondary loads).
External load on secondary at 400-volt tappings = 500 kVA.
Internal load on secondary between neutral and 400-volt tappings = 368 kVA (resultant of two secondary loads).
Load on 400–600 volt winding = 300 kVA (condenser load).

Where new step-down transformers are necessary, either as separate units or to bank with existing transformers, and in addition a condenser is required, it is possible to overwind the secondary of the transformer to give the most economical voltage for the condenser. By this means the auto-transformer is avoided and the whole scheme simplified, a considerable monetary saving being effected. The overwinding is a comparatively inexpensive addition to the transformer, and need of

low-tension busbars in each substation feeding industrial load, sufficient condenser capacity to neutralize the magnetization current of the whole bank. Condensers connected in this way would cut down the losses in transmission and reduce the wattless load on the alternators in the power station, and might in many cases enable one set to be shut down. In addition, an overall general improvement in the power factor of the system would be effected at load times, and a small but additional

benefit would be the increased, useful kVA output of the transformers in the substation. Such a scheme should not in any way interfere with the improvement of power factor by the individual consumer.

The static condenser is a very flexible apparatus and may be connected to the circuit in any convenient position on the load side of the meters. The condenser may be put across the main switchboard, the sub-distribution board, or the motors themselves, the further out on the load end of the feeder the better, provided the installation is correctly designed.

A great advantage of the static condenser is its mobility; it can be put down at the end of an overloaded circuit, but if later on this circuit is underloaded, it can be moved to another position as may be required.

When effecting improvement of a load comprising a number of squirrel-cage or slip-ring induction motors by means of a static condenser, full advantage can be taken of the diversity and the condenser be designed for the average conditions obtaining at the time of maximum load. Such a complete installation has a very high overall efficiency, comparatively low initial outlay, and small upkeep cost.

As to cost, the price per kVA of condenser capacity varies according to voltage, frequency, and climatic conditions, but, taking conditions in the United Kingdom and a three-phase 50-cycle supply at from 400 to 440 volts, the cost of equipments ranging in size from 100 to 300 kVA varies approximately from £3 5s. to £2 9s. per kVA, a good average figure being, say, £3 2s. per kVA.

Taking the average industrial load to be at 70 per cent power factor, it would be found that, when the power factor is improved to between 90 and 95 per cent, for every 2 kVA of condenser capacity the load is reduced approximately 1 kVA; therefore for every £6 4s. per kVA spent on condensers the demand is reduced 1 kVA. The capital expenditure on supply undertakings varies considerably, and a round figure of £40 to £50 per kVA may be taken. The installation of static condensers should therefore be a very sound and profitable investment for either consumer or supply undertaking.

Phase-Advancers.

The term "phase-advancer" is applied to apparatus built in the form of an a.c. exciter to improve the power factor of a slip-ring induction motor. Whereas in the auto-synchronous motor a d.c. exciter is used, which reduces the (synchronous) stalling torque to less than that of the equivalent induction motor, in the case of the a.c. exciter or phase-advancer the motor with which it works in conjunction retains all the characteristics of the induction motor.

The Kapp or oscillatory phase-advancer has been fully described in a previous paper, and reference has also been previously made to the rotary type of phase-advancer.

Fig. 3 shows a typical arrangement of a rotary phase-advancer, which may be driven either by a separate motor as shown, or from the main motor.

The characteristics of various kinds of phase-advancers of this type are shown in Fig. 4. Curve A is for a three-phase exciter with series characteristics, employing pure armature reaction and no commutating poles. Curve B is for an exciter similar to A, but provided in addition with stator excitation and commutating poles. Curve C is for a three-phase exciter with separate excitation and commutating poles.

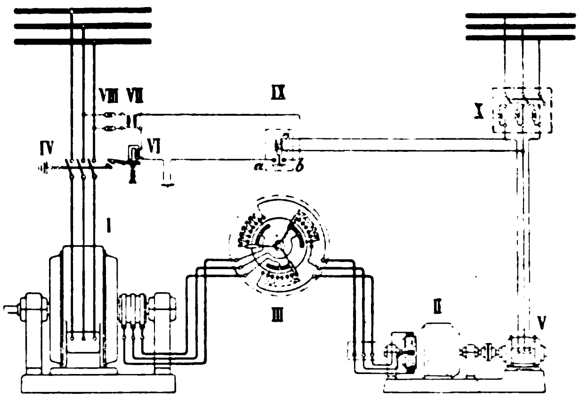

FIG. 3.—Diagram of connections of an induction motor with phase-advancer.

These a.c. exciters, which literally short-circuit the slip-rings of the induction motor and inject the necessary leading current into the rotor, may be built entirely without a stator, that is to say, as a simple d.c. armature revolved by a separate motor or other means. In other forms, a stator is provided with stator excitation devised by passing the rotor current in series through the stator windings.

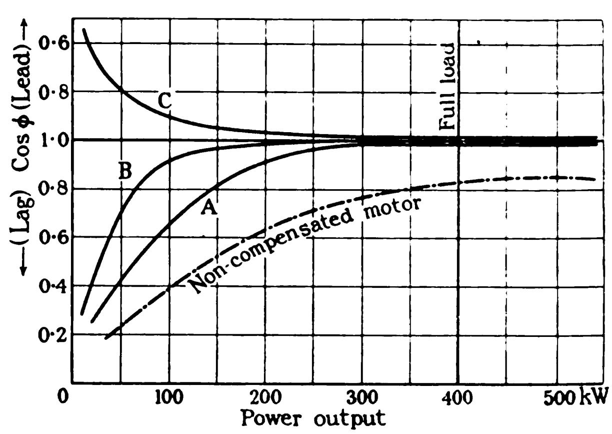

FIG. 4.—Range of compensation of various systems.

These types of phase-advancers have been used extensively on the Continent, but do not appear to have found much favour in this country.

Compensated Induction Motors.

A comparatively new type of induction motor capable of running at a high power factor at all loads is the so-called compensated induction motor. Among machines of this type is one built by the British Thomson-Houston Co., Ltd., and given the trade name of "No Lag." Characteristic curves are shown in Figs. 5 and 6 of a

$17\frac{1}{2}$ h.p. 1 000-r.p.m. 415-volt 50-cycle B.T.H. motor, but machines of this type can be built in sizes up to 200 or 300 h.p. for either two-phase or three-phase circuits up to 600 volts at any commercial frequency. The B.T.H. compensated motor has a commutator which enables the phase of the secondary to be controlled and, hence, the power factor to be corrected. The kVA handled by the commutator is very small, and so the commutator is of very small dimensions with simple and inexpensive brushgear. This compensated motor is as simple to operate as a plain induction motor, and standard starters as used for the slip-ring-type induction motor can usually be used. It is capable of giving as

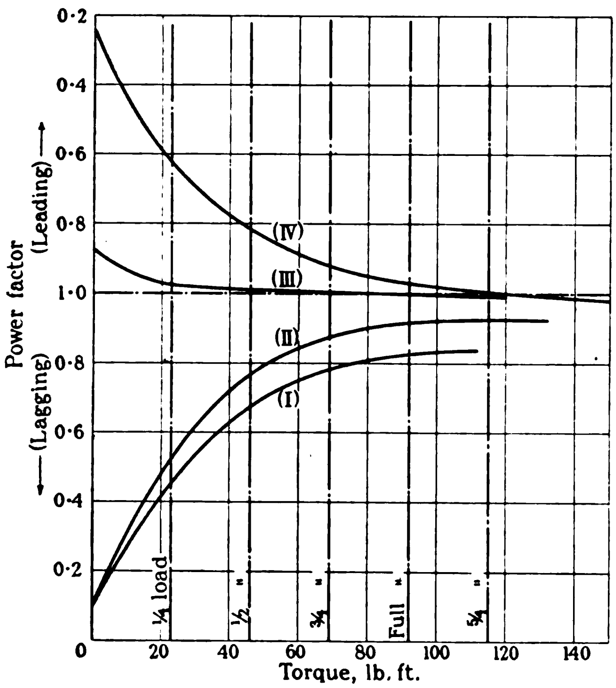

FIG. 5.—Power factor curves of compensated induction motor; $17\frac{1}{2}$ h.p., 1 000 r.p.m., 6 poles, 50 cycles.

(I) Power factor as induction motor.
(II) Power factor as compensated induction motor; min. compensation.
(III) Power factor as compensated induction motor; unity power factor.
(IV) Power factor as compensated induction motor; max. compensation.

large a torque at starting as the slip-ring induction motor.

Fig. 5 shows a typical power-factor curve of a $17\frac{1}{2}$ h.p. B.T.H. "No Lag" motor, and, as before stated, the power factor can be adjusted within the limits to give the figures shown by curve (III) or (IV). Usually the motor would be arranged to operate with characteristics such as those of (III), but, if desired, a leading power factor of 90 per cent at full load can be obtained, and in certain cases an even greater leading power factor.

Fig. 6 shows the speed and efficiency characteristics of this motor, from which it will be observed that they approximate to those of the plain induction motor. It will be noted that this is an asynchronous motor, so that for applications where a slight drop in speed with increasing load is necessary, or desirable, it is admirably suited. As no separate exciter or expensive switchgear is necessary this motor is less expensive than the auto-synchronous motor, and as it can be built in small sizes of the end-shield type it should have a wide field of application.

POWER-FACTOR TARIFFS IN FORCE IN GREAT BRITAIN.

A very large number of supply undertakings in Great Britain have adopted tariffs which provide a bonus for improved power factor, and it is reasonable to assume that the time is not very far distant when the great majority of undertakings supplying alternating current will adopt some form of power-factor tariff.

The power-factor tariffs in force in Great Britain may be divided into two main classes as follows:—

Class (*A*).—A two-part tariff incorporating a fixed charge per month, per quarter, or per annum, per kVA of maximum demand, with a running charge or flat rate per unit consumed.

Class (*B*).—A tariff which may be either of the two-part type based on the kW demand and the running charge per unit, or a one-part tariff based on units consumed only; in both cases, however, subject to a

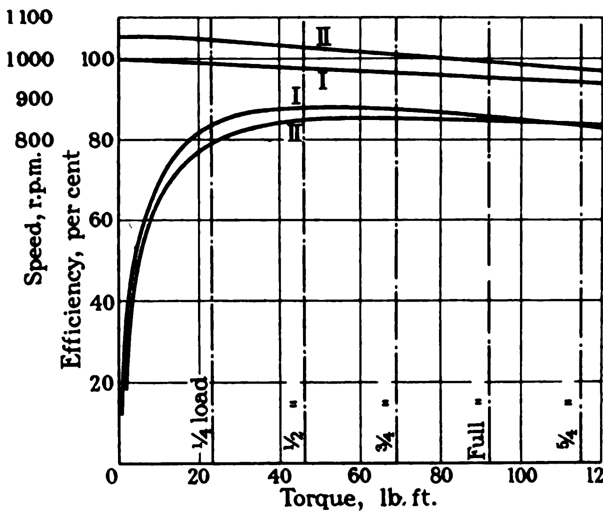

FIG. 6.—Efficiency and speed curves of compensated induction motor; $17\frac{1}{2}$ h.p., 1 000 r.p.m., 6 poles, 50 cycles.

percentage decrease or increase (bonus or penalty), depending upon the power factor of the load.

Typical power-factor tariffs in force in Great Britain to-day are as follows:—

Class (*A*). *kVA maximum demand.*

Tariff 1.—Straightforward kVA maximum-demand system. A fixed charge per kVA of maximum demand, which in the case of the majority of the undertakings may vary between the equivalent of £3 10s. and of £7 per kVA per annum. The general average appears to be about the equivalent of £5 per kVA per annum.

A number of supply undertakings adopt a quarterly, and in some cases a monthly, kVA demand charge about one-quarter or one-twelfth of the annual figures given above. A typical case of one large supply undertaking in the London area is the following:—

Fixed charge :—

	Per kVA per quarter
Demand to 50 kVA	£1 5s.
Demand over 50 up to 100 kVA ..	£1 3s.
Demand over 100 up to 200 kVA ..	£1 2s.
Exceeding 200 kVA	£1 1s.

In addition there is a sliding-scale running charge per unit metered, plus a coal clause.

Among supply undertakings adopting this form of tariff may be mentioned :—

The North Metropolitan Electric Power Supply Co., the South Metropolitan Electric Light and Power Co., Ltd., the Yorkshire Electric Power Co., the Wolverhampton Corporation, the Leeds Corporation, and many others.

Tariff 2.—In some cases an alternative tariff is quoted, and one typical instance, namely, that of the Bolton Corporation, is as follows :—

(*a*) *Fixed charge* :—

(1) Over 75 kW demand at 80 per cent power factor.

	Per kW per annum
Over 75 kW demand up to and including 100 kW	£3 18s.
For the next 100 kW demand or part thereof	£3 14s.
For the next 100 kW demand or part thereof	£3 12s.
For the next 100 kW demand or part thereof	£3 10s.
For every additional kW demand over and above 400 kW	£3 8s.

(2) Over 75 kVA demand.

	Per kVA per annum
Over 75 kVA up to and including 100 kVA ..	£3 3s.
For the next 100 kVA demand or part thereof	£3 0s.
For the next 100 kVA demand or part thereof	£2 18s.
For the next 100 kVA demand or part thereof	£2 16s.
For every additional kVA demand over 400 kVA	£2 14s.

(*b*) *Running charge* :—

Flat rate 0·34d. per kWh, based on coal at 10s. per ton, with an increase or decrease of 0·015d. per kWh per shilling per ton.

Tariff 3.—In this tariff the fixed charge is a kW charge, but varies with the average power factor of the load, and is the system adopted by one of the leading power companies in Scotland. It is as follows :—

(*a*) *Fixed charge* :—

	Per kW per annum
0 to 250 kW	£10
1 000 kW	£8
10 000 kW	£6

Intermediate demands *pro rata*.

(*b*) *Running charge* :—

0·4d. per kWh, flat rate, based on coal at 20s. per ton.

The above rate is based on a standard power factor of 80 per cent, and the fixed charges are increased or decreased inversely in proportion to the power factor, i.e. at 90 per cent power factor the fixed charge is eight-ninths of the basic figures ; at 60 per cent power factor it will be eight-sixths. The power factor is the average power factor obtained by the readings of a sine and cosine meter.

It will be noted that in all the foregoing tariffs the fixed charge only is affected by the power factor.

Class (B). Tariffs embodying power-factor bonus or penalty on total bill.

Tariff 4.—One important supply undertaking in this country has a two-part tariff with kW demand and unit charge, and the following bonus or penalty is incorporated in their rates :—

Per cent	Bonus or penalty per cent
Power factor 95 and over	− 8
Power factor 90–95	− 7
Power factor 85–90	− 5
Power factor 80–85	− 3
Power factor 75–80	− 1
Power factor 70–75	+ 1
Power factor 65–70	+ 4
Power factor 60–65	+ 7

It will be noted that in this case the basis is a power factor of 75 per cent.

Tariff 5.—The following tariff adopted by one supply undertaking is a variation of Tariff 4. The charges are as before on a kW and running-charge basis, but the power factor adjustment is as follows :—

Basic power factor: 80 per cent.

Bonus. For each 1 per cent improvement in power factor above 80 to 90 per cent the overall charges, that is, both running charges and unit charges, will be reduced by 1 per cent. For each 1 per cent from 90 to 95 per cent the charges will be reduced by ½ per cent.

Penalty. For each 1 per cent the power factor is below 80 per cent the charges will be increased by 1 per cent.

Tariff 6.—A further variation of Tariffs 4 and 5 is as follows :—

For a power factor maintained at 85 per cent and over, a discount of 5 per cent on the total bill.

For a power factor maintained at 90 per cent and over, a discount of 7½ per cent.

Some undertakings have adopted a similar tariff but with different discounts.

It will be seen that the tariffs divide themselves as indicated in the foregoing into two broad classes, those which give a bonus for reduction in kVA demand only and no bonus on the running charges, and those which give a bonus on the total bill, that is, the capital charges and running charges.

It may be safely said that the majority of supply undertakings are favouring the kVA demand tariff, owing, no doubt, chiefly to its simplicity, in that a satisfactory meter can be provided to record the kVA

demand and an explanation of the term "power factor" is not involved.

Those supply undertakings which charge, on kVA demand, the equivalent of about £5 per kVA can be shown to offer the necessary inducement to the consumer to improve the power factor by the various means available at the present time, and in the majority of cases quite a good return on the capital expended in power-factor-improving devices can be shown. For this reason, where this type of tariff has been adopted it will be found that the great majority of the consumers on such systems have set about improving their power factors, with a resultant overall economy and a relatively low average price per unit for the general industrial user of electric power.

In the case of Class (B) tariffs, several difficulties are met with in getting the consumer to put in plant for the improvement of power factor, the chief of which are as follows :—

(1) In the case of an overall bonus or penalty on the power-factor supply bill it follows that a consumer running with a relatively high load factor has a large supply bill compared with the low-load-factor consumer, both running with the same maximum demand and power factor. To improve the power factor would require the same condenser capacity in each case, but the consumer with high load factor would get a proportionately greater saving than the one with low, and the inequity of this type of power-factor tariff is very evident.

(2) In those cases where a bonus is given for improvement of power factor above definite limits, such as 85 and 90 per cent, the objections referred to in (1) above also apply, but in addition there is another serious objection, and that is that the consumer with, say, 83 per cent power factor can, with a comparatively small condenser, correct to either 85 or 90 per cent power factor and obtain the bonus, but the consumer with a very low power factor, say 50 per cent, would have to correct right up the scale to, say, 84 per cent without getting a penny piece by way of bonus, in other words the low-power-factor consumer would have to put in such large condenser capacity that in the majority of cases it would not pay.

(3) This type of tariff involves an explanation of the term "power factor," and it will be generally agreed that the less explanation of power factor one has to give to the consumer the better.

Metering.

The two chief methods of metering adopted in Great Britain may be illustrated by the two vector diagrams shown in Fig. 7. Meter A, in both cases, is a cosine meter or ordinary kWh meter, whereas meter B integrates the kVA-hours and, when fitted with a maximum-demand indicator, gives the true kVA demand. Meter C is the so-called sine meter, and integrates the wattless-component kVA-hours. Such an instrument is not usually fitted with a demand attachment.

(A) *For kVA demand tariff.*—For small loads the thermal demand-indicator is generally adopted, this instrument being reasonably accurate, and is usually a secondary instrument working across a current transformer. There may, of course, be three instruments for a three-phase load.

The new Hill-Shotter voltage-compensated kVA demand indicator built by Messrs. Aron Electricity Meter, Ltd., is an interesting development; whilst the instrument is comparatively costly, its introduction is in the majority of cases warranted for larger loads, where extreme accuracy is of such importance.

The foregoing instruments are purely for the purpose of arriving at the kVA maximum demand, and it will be appreciated that the thermal demand-indicator is governed by the current only and is therefore calibrated only for the declared pressure, whereas the voltage-compensated Hill-Shotter type of meter gives an accurate reading in kVA demand. In both cases there would, in addition, be the usual meter registering B.O.T. units.

The combination of these meters provides a simple equipment which can be read by any consumer and does

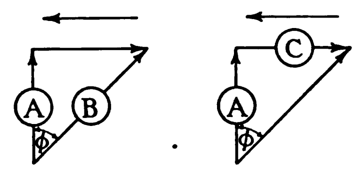

Fig. 7.

not involve any intricate mathematical calculations to arrive at the power factor.

(B) *Tariffs embodying power-factor bonus or penalty on total bill.*—In this case it is usual to employ the cosine or unit meter in conjunction with a sine meter as (C) above. The sine meter is quite a simple type of instrument and is constructed to record accurately the apparent kVA-hours of the wattless component of the load. Such instruments may be either single-phase, two-phase, three-phase or three-phase 4-wire, and would in the usual way be secondary instruments working in series with the unit meter off the current transformer. At the end of the period the integrations of the unit meter and the wattless-component meter are noted, and from the ratio of these two can easily be determined the so-called average power factor of the load. Taking as an instance the following :—

Unit meter recording	..	1 000 kWh
Sine meter recording	..	882 apparent kWh

$$\tan\phi = \frac{882}{1\,000} = 0 \cdot 822$$

$$\cos\phi = 0 \cdot 75 = \text{power factor}$$

The sine meter can be fitted with a ratchet mechanism to prevent its reversal when the power factor is leading or if static condensers only are left on circuit with the load off. In the case of one large power company it is customary not to fit such ratchets but to allow the watt-

less component meters to be reversed. It may here be pointed out that consumers are allowed to reverse the sine meter in order to encourage the connection of static condensers and the like during no-load hours, to neutralize the heavy lagging wattless component of the load on the system due to the magnetization of idle transformers, etc.

A similar average-power-factor result is obtained in many cases by the two single-phase kWh meter method

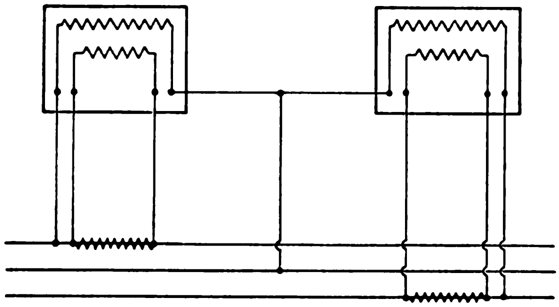

FIG. 8.

in which the instruments are connected up as shown in Fig. 8. The readings of the meters give the following :—

$$\tan \phi = \frac{(W_1 - W_2)}{(W_1 + W_2)}\sqrt{3}$$

W_1 being the reading of the one meter and W_2 that of the other. From the formula it is possible to ascertain the angle of lag, ϕ, and thus the power factor.

It is suggested that neither of these two systems would be understood by the great majority of industrial users of a.c. power.

Either of the foregoing systems of metering for average power factor may be considered to be sufficiently accurate for the purpose of arriving at the bonus or penalty in the case of those tariffs giving a percentage reduction or increase on the total bill, but to apply this system of metering in a case where the power factor is obtained for the purpose of determining the ratio of kW demand to the kVA demand is not strictly equitable, as the average power factor must of necessity be lower than the power factor at the time of maximum load. As the kW charge would be that occurring at maximum load it would mean that this charge would be increased in accordance with the power factor based on average conditions, whereas it should be the power factor at the time of peak load.

Other methods, which may be regarded as not very satisfactory, of arriving at power factor are the periodical spot test and the use of an indicating power-factor meter.

A spot test is obviously a very insecure basis to work upon, as conditions may vary from day to day, or from month to month, and it is impossible to be continually spot-testing.

The power-factor indicator has somewhat the same disadvantages, as the meter reader cannot be continually visiting the consumer to ascertain the power factor under varying conditions; also the commercial power-factor indicator of to-day is hardly an instrument in which any very great reliance as to accuracy can be put.

The correction of low power factor is one of the few important economies remaining to be effected, and there seems little doubt that, converted into £ s. d., low power factor is resulting in enormous losses to supply undertakings, not only as regards capital charges but also running charges, and the losses are being borne by the industrial user of a.c. power. Admittedly, the consumer is responsible for the power factor of the load, but it behoves every undertaking supplying a.c. power to make it worth while for the consumer to raise his power factor and thereby effect a general reduction in the electricity charges, thus ultimately benefiting industry in general.

DISCUSSION BEFORE THE INSTITUTION, 4 FEBRUARY, 1926.

Mr. R. O. Kapp: This question of power factor has received a good deal of attention during the past few years. A great many papers have been read and discussions have taken place on the subject, and one might think the question had been exhausted, yet here we have two papers each treating one aspect of the matter and each containing something new and important. Mr. Clark's paper deals very largely with the question of tariffs, and that is a most important and complicated problem. Broadly speaking, there are two aspects from which the problem of tariff-making can be studied. I propose to call one aspect the accountant's point of view. It is that of finding exactly what a given consumer or a given class of consumers costs, and devising a tariff so that precisely that amount, plus a reasonable profit, shall be obtained. That, however, is not the whole story of tariff-making, as everyone knows who has to deal with the subject. There is another aspect, which may be called the salesman's. The salesman has to consider such aspects of the matter as cannot be expressed strictly in terms of pounds, shillings and pence. He has also to consider—and this is a very important point—the mentality of the consumer. Every tariff is based as nearly as possible on the accountant's point of view, but also takes the salesman's into account. I think perhaps that Mr. Clark's paper does not give as much emphasis to this latter as the practical tariff-maker would have to devote to it. I should like to mention, therefore, two points from the salesman's point of view which have to be considered in connection with power factor. One of them, which Mr. Clark mentions, though without a great deal of emphasis, is the question of voltage regulation. A bad power factor means bad regulation. This point is important on installations containing a number of transformers, and more particularly on any system having a considerable mileage of overhead line work at a low voltage. In order to keep within any given limits of voltage regulation, the number of kVA-miles transmitted by any particular line must be restricted. Now, at a

power factor of 0·8 the kW-miles that can be transmitted for a given voltage-drop are, broadly speaking, about half what can be transmitted at unity power factor. That is quite an important point. In a footnote at the end of that section of Mr. Clark's paper which deals with the charge for wattless component the author gives an illustration of two consumers, and from other points of view he shows that the technical benefit to the supply undertaking would be identical with certain adjustments of power factor, but he omits to say that one consumer would give more benefit to the undertaking than the other, from the point of view of voltage regulation. It does not mean that in order to make up for the inferior regulation on the lower power factor one must increase the cross-section of the copper conductor. That is only a partial help. If a line is approaching the limits of permissible loading from the point of view of voltage-drop, it means that either boosters or another line must be installed. Probably, on the ground of expense, one would install boosters. Not only the prime cost but the losses of such regulators are important, as appreciable iron losses are going on all the while. Bad power factor, therefore, adds something to the cost over and above what the accountant's method, as mentioned in this paper, would take account of. There is one remark in the early part of Mr. Clark's paper which I should like particularly to stress. He says: "But the fact that supply undertakings working with a tariff of this kind are not fully satisfied with their station power factor, however low it may be, is surely evidence that this tariff departs seriously from the ideal." That, of course, is true. The ideal tariff is not only an accountant's but also largely a salesman's tariff, and this must take account of mentality, and by mentality, to speak crudely, I mean the ignorance of the consumer. There are two ways of meeting this particular point of the ignorance of a consumer with regard to power factor. One is to educate him; but that seems rather a hopeless task. If the tariff is devised on such lines that a consumer receives a bonus for an improved power factor it may be possible to educate him. If, however, the tariff is on the lines that the consumer pays a penalty for a bad power factor, his mind will work slowly and he will have great difficulty in understanding what power factor means. Another way of dealing with the problem is to devise such a tariff that the consumer need not know anything about the power factor at all; and from this point of view it seems to me that a two-part tariff, composed of a kVA maximum demand, plus a unit charge, is probably most likely to meet the case. The consumer does not really know the difference between kW and kVA. He can think of one or the other in much the same terms, and if he is in the habit of paying for kVA maximum demand and is told that by putting in a power-factor-improving device he will reduce his current bill, he will not need to worry about power factor and all these troublesome mathematical problems. He will have a vague idea that he is being instructed how to improve the efficiency of his motor, and he will think that this power factor device will reduce his losses. He will not understand it, but he will do the right thing to the benefit both of himself and of the supply undertaking. There is one other point with regard to the accountant's tariff which I should like to mention. Mr. Clark suggests a three-part tariff which, however, eventually boils down, from the consumer's point of view, to a two-part tariff after all, because he has only two meters. It is assuming that the two-part tariff is an accountant's one, i.e. that it is calculated on a basis of accurate costing and that the power factor adjustment that would be made by this very ingenious biased meter would introduce a further refinement into the costing. I am not at all sure that the average two-part tariff is completely and wholly an accountant's tariff. I believe that the figure given in the paper, for instance, which is a very fair average figure of £5 per kVA maximum demand, plus 0·5d. per unit, is not justifiable on the costing basis only. On this basis the demand part of it would have to be higher and the unit charge lower, because in making up most two-part tariffs quite a lot of factors are attributed to the running costs which should, more strictly speaking, be allocated to the fixed charges. I believe that nearly the whole of the wages in a power station is a fixed charge. Quite a large part of the coal bill is a fixed charge. Radiation losses through steam pipes, and losses in accessories, are fixed charges. Even the coal-handling charges are largely fixed, because a station has to have a staff for that purpose whether they are working full time or not. Too close an approximation to strict costing, therefore, seems hardly practicable. In the early part of the paper the author says: ". . . the diversity factor of wattless component is in general much lower than that of energy component." I should almost think that it would be the other way round, and that there would be less variation amongst the energy components than amongst the wattless components. It may be a question of the way this term "diversity factor" is taken. It is generally defined as a figure greater than unity, but possibly in his paper the author took it as meaning a figure less than unity.

I can confirm what Mr. Dorey says as to the risk of resonance being negligible in condenser installations. I was particularly interested in his development of "pole-type condensers." The importance of overhead lines, particularly of rather low voltage, makes this pole type very useful. There appears to be a big future for something of the sort. There is a tendency for more rural electrification, and I do not see how that will be possible on a commercial scale unless we have some cheap means of improving the power factor of the low-voltage overhead lines which will no doubt be used. There is one type of consumer who is very troublesome to an industrial undertaking, and that is the user of a.c. fans. These have a particularly bad power factor. Consumers in tropical countries are usually very scattered over a large residential area and there is generally a considerable distance of overhead line, so that the question of power factor is quite important. I should like to ask Mr. Dorey whether he thinks that an individual condenser to improve the power factor of either a single house or of each fan is a practicable proposition. I had occasion to estimate that some years ago, before condensers had reached their present stage, and I found then that the first cost was such that the installa-

tion of such condensers would not be commercial. One point which Mr. Dorey does not mention, but which I think is quite important with regard to these static condensers coupled with transformers, is that an installation of this kind is generally put in well in advance of the loading. One puts in one's transformer and condenser installation to meet the load expected in three or four years' time, and, to start with, there is very little. However, the condensers have to be of the full kVA capacity of the final installation, and, as Mr. Dorey knows (because he and I collaborated on a scheme of that sort), what has been done has been to tap the transformers so that the voltage by which the condensers were supplied could be increased year by year as needed, this increase in the voltage being equivalent to an increase in the injected leading kVA given by the condensers.

Mr. S. H. Hart: The frequent articles appearing in the technical Press and the discussions which have taken place, both in this country and abroad, as to the best methods of dealing with the difficulties arising out of low power factor, are a clear indication of the importance, to both supplier and consumer, of the subject now under discussion. There is no doubt that this question is steadily becoming more serious and is keeping the cost of electric supply considerably higher than it would be with good power factor. The problem of low power factor may be viewed from three different points, namely: (1) The avoidance of low power factor by a judicious choice of apparatus; (2) the use of special apparatus, the sole aim of which is to improve the power factor; and (3) the correct method of charging consumers who use a large wattless component. With regard to the avoidance of lower power factor, it is universally agreed that the main difficulty is the induction motor and all small machines of this type. In the case of the induction motor, the design plays an important part in determining the power factor at which it will work, the main factors being: (1) Maximum torque at full load; (2) speed; (3) type of rotor (squirrel-cage or slip-ring); and (4) output margin. When a motor is installed with a greater pull-out torque than is needed, the result is a considerable reduction in power factor at the normal working load. The speed of an induction motor plays an important part in determining the power factor; the lower the speed the lower the power factor, and hence it is advisable to run the motor at as high a speed as possible. The squirrel-cage motor has a much lower leakage coefficient than the slip-ring motor and hence has a higher power factor, and for this reason it is advisable to install squirrel-cage induction motors. Another important factor causing a low power factor is the installation of motors of which the normal output is two or three times the service requirements; it is obvious that the remedy for this is to use motors of which the capacity is determined by the usual load they have to carry and not by the possible maximum.

Mr. Dorey states that the rotary condenser compares very unfavourably with other forms of power-factor-improving apparatus, such as static condensers, but in the case of a low supply frequency it is cheaper to install rotary condensers than static condensers, as the capacity required per kVA of the latter varies inversely with the frequency at which it operates, whereas in the case of rotary condensers the frequency determines the number of poles that must be used for a given speed, and the effect of having a low supply frequency (e.g. 25 cycles instead of 50) upon the cost per kVA is not very marked. At the present time there are divided opinions as to whether the supply undertaking or the consumer should be responsible for the improvement of power factor. In the case of large consumers the adoption of a scale of charges sufficiently favourable to the maintenance of a high power factor will result in the consumers recognizing that the use of power-factor-correcting apparatus will prove to be a sound financial investment, especially if, as in the case of phase-advancers applied to the rotor circuits of induction motors, other improvements, such as increased breaking-down or "stalling" torque, reduction in stator current and hence increased continuous rating, are obtained. With small consumers it is probable that both the consumer and supply undertaking will work in conjunction for the improvement of low power factor. In any case the undertaking should be ready to supply the necessary machinery for the improvement should the consumer be unwilling to do so. The best way in which the undertaking can help is by having a favourable tariff in operation. It has been suggested that new power consumers should be advised to install apparatus to correct the power factor, and if they take a leading power factor a rebate should be allowed on their account. It seems to me that the most suitable tariff is that based on the kVA maximum-demand system with a flat rate per unit consumed.

Mr. W. B. Woodhouse: There is no doubt that idle current does involve extra cost to the supply undertaking, and consequently the consumer must pay for it. The commercial question is: What is the best way to make the consumer pay for idle current? That, I think, rather turns on the answer to the question: Is it more easy and economical for the undertaking to correct for power factor, or for the consumer to do so? Generally speaking, I think it will be agreed that the small consumer cannot be troubled with a matter of this kind. If his installation has a power factor that is less than unity, then the supply undertaking must do the correction. With the large consumer, however, the position is different. A great many large consumers can, by attention to their installation, or by putting in some means of correcting for idle current, increase the power factor to something approaching unity, and therefore the tariff in which the charge is based on kVA is a good one, because it affords a direct inducement to them to improve the power factor. In Yorkshire we have charged on the kVA basis plus a unit charge since we started the supply in 1904, and the effect has been striking, because in many cases the consumer has realized the very large saving that can be made. I know of one case where the saving was something like £2 000 a year. In another case the consumer saved £6 000 a year on his energy bill—a very important consideration. The method of charging for idle current brings up another point: Is the consumer to be charged with the idle current at the time of maximum demand

—which, after all, is the time when the plant and cables are most heavily loaded—or is he to be charged on the basis of the idle ampere-hours ? I think that, generally speaking, the method of charging on the basis of idle current at the time of maximum demand is more in accordance with the actual cost to the supply undertaking. Its drawback is that there is at present no quite suitable meter for ascertaining this charge. The thermal indicator, though it is a very excellent instrument, and though it agrees very closely with the heating characteristic of the plant and cables, is yet independent of voltage, and if the voltage is not kept constant the indication of kVA is not very accurate. Where a charge is made for maximum demand in kW we have in use a very accurate instrument, the Merz attachment to the ordinary watt-hour meter, accurately giving maximum demand over a predetermined interval of time. What is needed is a similar instrument to give kVA in the same way. The method of summing idle ampere-hours or volt-ampere-hours is, I think, open to some objection, in that the costs of the undertaking are not in proportion to that total; they are more nearly in proportion to the idle current at the time of maximum load.

Mr. R. A. Chattock: It seems to me that the question of correcting for power factor depends very largely on the nature of the load that the supply undertaking is called upon to give. Comparing an undertaking such as mine in Birmingham, where the majority of the supply is given by direct current, with an undertaking such as Mr. Woodhouse is in charge of, where practically the whole of the supply is alternating current, my particular undertaking is placed in a much more favourable position with regard to power factor than his, because we have installed in the district a considerable number of rotary-converter substations which can be used for correcting the power factor on the main trunk lines that supply them. The distributing cables to the a.c. consumers which run from those substations are subsidiary lines and are practically never loaded to their full capacity. Whilst it is very important to keep the trunk lines well loaded because they are the main carriers and are the most expensive lines we have to put in, it is necessary to see that there is a minimum wattless current passing through them, so that by arranging the rotary converters in these substations to run with a leading power factor one can correct to a very large extent the most important part of the network. In that way it is not so attractive to us to get the consumers to correct on their own premises as it is to an undertaking such as Mr. Woodhouse has described. Whilst it is true that we do offer a discount for a certain percentage of power factor, it has not really attracted the consumers in Birmingham to any great extent. We have some large consumers who correct, but at the present time it would not be to our interest to increase the discount in order to produce a greater correction than there is at present. The time may come, of course, when the a.c. load becomes very much greater than the d.c. load, but I wish to point out that it does not follow that the problem of one undertaking is the same as that of another undertaking.

Mr. Dorey describes the installation of condensers in rural districts. I have had some experience with a condenser on the premises of a large consumer in connection with power load, and in that particular case we found that when the condenser was left on at night-time when the works were shut down, as was done on one or two occasions, it gave a serious leading power factor to the system and upset our regulation in the stations when there was only a small percentage of load going out. We had to be very careful not to allow the condenser to be left on when that consumer was not using his motors. If in a rural district we have a number of condensers left on the line all night when there is practically no load, I am afraid we shall get very considerable leading power factor, and the regulation may be very difficult to arrange for. However, that will, of course, have to be gone into when the thing is developed, but I should like to know whether Mr. Dorey can tell us anything about the experience in New Zealand, where I believe condensers are being used in rural districts.

Mr. L. W. Migotti: In Buenos Ayres we supply roughly 500 million, in Rosario some 60 to 70 million, and in La Plata some 20 million kWh. In those three undertakings I do not think we have one consumer of any description who is charged on a kVA basis, whether this be assessed by an integrating or a demand meter. The only people we have met who would take the slightest interest in this sort of thing were some of the representatives of the British-owned railways. We are, however, in the fortunate position of being able to correct our power factor, owing to a large tramway load and to districts we supply with direct current. The power factor over all generating stations is certainly not lower than 0·93 during the day and 0·97 during the peak load, which of course is the most important time. The problem of a low power factor, therefore, does not cause us much anxiety at present, although it may do in time. Our method is to make a complete study of the tariff question each year, and to put down against each class of client the minimum rate we expect to receive in each case, and on these data we base our arguments to our clients. I think that we should do much better, in general, if we took charge of the power factor question and, if we found a consumer with a particularly low power factor, to include that in his tariff. He would then not know whether he was paying on a kVA or any other basis.

The point Mr. Clark has made in connection with the interchange of current between two undertakings, is certainly very important, because that opens up quite a different view of the matter. There is undoubtedly room for discussion of tariff questions between two undertakings supplying one another with energy. As far as the ordinary client is concerned I think we should find it much better to take a commercial view of the problem and either correct the power factor ourselves or ask those who have designed automatic substations to produce automatic power-factor-correcting plant so that the question of condensers or other apparatus left on the line during the time of no load will disappear. I feel that consumers should not be worried with questions of power factor unless they are fully able to understand and discuss this matter.

Mr. A. H. Bennett: I think that Mr. Clark in putting

forward his three-part tariff is trying to prove on paper something which is not really necessary; in practice, as Mr. Woodhouse says, a two-part tariff is all that is required. We find very little difficulty in getting consumers to accept this two-part tariff. We do not try to explain to them the full effects of power factor, in spite of the help we have had from one of the authors on methods of explaining it. What we do is to show them in pounds, shillings and pence exactly what it means to them. A very simple illustration will bring it home; on the average 50- to 200-kVA installation, working with Mr. Dorey's figures, it can easily be seen that a consumer can, if he has a power factor in the neighbourhood of 0·7 and wishes to improve it to 0·9, save the cost of new condensers in approximately 18 months. In other words, we find on the North Metropolitan Electric Power Supply's system that if we want a consumer to put in a condenser we have only to offer him that condenser on hire-purchase terms and he will actually save enough on his quarterly bills to pay for the apparatus. After two years he is entirely in pocket. On page 625 Mr. Clark points out that our aim is to sell electricity, not energy, but I am afraid I do not agree with him. The public wants energy and it is up to us to supply energy produced from coal or in other ways in the form which is most suitable and economical for the use of the public. Mr. Clark says we are not satisfied with the working tariff. That is certainly the case, but I think it is only a matter of a very few years now, using examples such as I have quoted on the hire-purchase basis, before we shall convince all consumers that it is worth while for them to put in the necessary apparatus to improve power factor to something over 0·9. We have very largely done so already, and I think Mr. Woodhouse has also. One of our consumers has a 1 200-h.p. rolling motor the power factor of which, corrected by static condensers, is practically unity from one-quarter load, which is the light running load of the mill, to full load.

Mr. P. M. Baker: I feel that a tariff which requires the consumer to understand the meaning of power factor is useless. I have never yet met a consumer who understood what I meant by power factor. I think, therefore, that we must aim at something which does not require him to grasp that somewhat abstract idea, and for that purpose I think the kVA charge, plus a unit charge, is better than most other forms of tariff. It seems to meet the case more or less satisfactorily and it does not involve any very serious amount of explanation. It seems hopeless to try to make an ordinary consumer understand that the product of volts and amperes does not always represent power.

Mr. J. H. Johnson: It seems to be difficult to get unanimous agreement on the question of charging on a kW or kVA basis. There are many consumers who are charged on a kW basis and who are a source of great trouble to supply undertakings. Some of these consumers have a power factor as low as 0·4. Naturally it is to be expected that any supply undertaking would desire to raise the power factor of such a consumer or on that particular feeder, to make the consumer pay extra charges. On investigating a number of these cases it was found that the low power factor was due to the use of a number of small induction motors which were working at about one-third load. I mention this particular point as in the early part of Mr. Dorey's paper he refers to the use of ball and roller bearings for induction motors and points out very definitely that a reduction of the air-gap will increase the power factor. That is quite true, but there are limitations, because in these days of keen competition one has to remember that there is the workmanship to be considered. The increased diameter of shaft and the rings inside the bearing are matters for consideration, as they affect reliability. Mr. Dorey refers to static condensers; these certainly serve a very useful purpose, but they have their limitations. The power factor cannot be varied with changing load, as in the case of a rotary condenser or a synchronous motor. The first cost also must be considered, whilst above all there is what I may call the commercial value of the motor when it is no longer used for the duty for which it was first required. A comparison between a static condenser and an auto-synchronous motor which will give mechanical power as well as leading or lagging power, as may be required by load conditions, will show that the latter is a more serviceable and commercial proposition as compared with the former. Mr. Dorey refers to the Clyde Valley Electrical Power Co. and speaks about leaving the static condensers in circuit all night and during the week-ends, but I believe in that particular instance there are three generating stations, and the trouble was not in the actual load on the supply, but on light loads and during week-ends. It was found that the power factor was so low that if it was raised by installing static condensers on consumers' premises and left in circuit, it was possible to shut down the power station on that particular district. This cannot, however, be put forward as an advantage which may be obtained generally. It has been pointed out by various speakers in the discussion that there is a certain disadvantage, especially in rural districts, in having at the end of a feeder a consumer with a varying load. With a synchronous motor the power factor could be adjusted by the excitation, this not being possible commercially with a static condenser. Recently I had occasion to supply an auto-synchronous motor with a lagging power factor of 0·45, simply to compensate the leading power factor on that particular transmission system. Reference has been made to phase-advancers and to the compensated induction motor; the latter has limitations, in that it is inadvisable to have a supply voltage higher than about 600. It is only commercially possible at present in sizes from 5 to 100 h.p.; above that size it compares unfavourably with an asynchronous-synchronous, or auto-synchronous motor. In the Crompton auto-synchronous motor, with a two-phase induced winding, the motor can be built for high tension or extra-high tension, and the neutral of the induced winding earthed. In addition, provided the exciter is large enough, it is possible to arrange for the same kVA capacity to be absorbed either with a leading or lagging power factor. To the power user in ordinary industrial concerns this is a point of considerable importance if charged on a kVA basis. In London there are two auto-synchronous motors now running, each equivalent

to 2 800 h.p. at 360 r.p.m. with a 0·9 leading power factor and operated by unskilled labour. The use of condensers in this particular installation would have been uncommercial. Auto-synchronous motors are now applied to the driving of every form of industrial machinery of the heaviest class and with a starting torque of 2 to 3 times that of full load, synchronizing automatically.

Mr. H. S. Ellis: Has Mr. Dorey considered the merits of the Maxigraph kVA demand indicator, which I believe is made by Messrs. Landis and Gyr and which I have used quite successfully as an alternative to the other makes of kVA demand indicators referred to in the paper? This is an instrument which I think can be depended on to register kVA correctly, although perhaps the range of power factor through which the instrument is correct may not be so wide as the range of other instruments. However, it has one advantage which was not apparent in other instruments which we carefully considered in one particular case I have in mind. A supply of electricity in bulk is obtained from a feeder which runs through the bulk-supply area, and it is necessary to have a set of meters at each end of that area, the reason being that the feeder is continued beyond the bulk-supply area to a district where other supplies are afforded. In this case it was necessary to synchronize the meters at each end of the feeder in order to ascertain the actual demand of the bulk supply at any particular time during any particular period, which meant that the kVA indicators had to be of the recording type and such as could be synchronized. This quality is found in the Maxigraph indicator, and as the demand is recorded at the end of any predetermined period, say 20, 30 or 60 minutes, or whatever the period required may be, it is a very simple matter to bring the two charts together and subtract the readings of one from the readings of the other. I am not aware that there is any instrument other than the Maxigraph which would satisfy this condition.

[Mr. Dorey's reply to this discussion will be found on page 652. Mr. Clark's reply will be published later.]

North-Western Centre, at Manchester, 2 February, 1926.

Mr. J. Frith: We should no longer expect the supply undertakings to give us wattless current free, but I do wish to make a strong protest against any more complicated tariffs. I know, from experience, that the complication and treachery (in appearance at any rate) of these tariffs does militate against the use of electricity. Consumers do not like them because they do not understand them. In metering for power factor, why not specialize on the 2-wattmeter method? It gives the consumer some idea of what is happening. He is shown two ordinary unit meters and is told that his total consumption is the sum of the reading of these two meters, that the greater the difference between the two the lower his power factor is and that when the power factor is unity the two meters will read alike. The papers might with advantage have dealt at greater length with the difference in actual use between the synchronous motor and the static condenser for correcting power factor. One or other of those is, I think, the method which will be adopted. The high-power-factor motors mentioned, besides costing more and being less efficient, all have commutators which are much worse than those of the old d.c. motors. I advocate the use of large squirrel-cage induction motors; a supply undertaking need no longer object to these. There is no doubt that static condensers are more efficient than synchronous motors. (In parenthesis I wish to protest against Mr. Clark's use of the term "efficiency"; kW loss expressed in terms of kVA input is not efficiency.) The synchronous motor is, of course, the easier to adjust, for which purpose a power factor indicator showing the corrected power factor should be placed near to it. With a static condenser no such control is possible unless it is made in smaller units switched on and off separately; this, of course, adds greatly to the expense and trouble. I should like to know if the supply undertakings are content with the main condenser being switched on and off so as to keep the readings of the two watt-hour meters approximately the same. This seems to be the only way, especially if the consumer is given no credit for leading power factor—which very often he is not. With regard to the question of resonance it seems to me that when the power factor is unity, $L\omega = 1/(k\omega)$, which is exactly the condition for resonance. What other resonance is there in the circuit? I wish to protest against the compulsory use of auto-transformers. When we wish for a motor to work on a 400- or 440-volt supply we are not told by the makers that they only make a 600-volt motor and that we have to use an auto-transformer with it to get the right voltage. I have seen these condensers being made, paper being used, and have been told that one thickness of paper is not enough for 400 volts and that two thicknesses will be sufficient for 600 volts, and I am still not convinced.

Mr. L. Romero: I am rather surprised that Mr. Clark advocates a tariff based on the kVA of maximum demand. This means that the consumer is charged just the same for kVA as he is for kW and it seems to me to be altogether wrong. If it really costs as much to supply kVA as it does to supply kW why have not the supply undertakings improved the power factor themselves; they would have effected a very large saving in doing so. In my opinion the financial effect of low power factor is considerably exaggerated. I have just worked out, on the tariff that the author gives, a concrete case—a power consumer with a maximum demand of 100 kW at 0·5 power factor, using 200 000 units per annum. The annual cost to him for power is £1 447. He then installs a condenser at a cost of £375 which raises his power factor to 0·9 and thus reduces his annual bill for power to £950. It is perfectly obvious that the saving of £497 on his annual bill will not be reflected in the saving made by the supply undertaking; this will be nothing near that amount. The author says that item (*c*) of his tariff is not quite ideal. I should go further and say that it is distinctly inequitable. It is apparently based

on the idea that the whole capital cost of the undertaking varies with the kVA load, but of course it does not do this at all. The principal items which do not vary with power factor, or, if they do vary it is only to a very small extent, are, in the power station, land, buildings, coal- and ash-handling plant, boiler plant, turbine house plant except generators, and generator main switchgear. At the consumer's end of the line where the supply is at extra-high tension, the cost of the meter and e.h.t. switchgear on the consumer's premises, and of the e.h.t. service and main supplying individual consumers, will not be affected by power factor except in the case of very large consumers.

Mr. Dorey says that the system of varying the whole amount of a consumer's bill according to power factor is very inequitable as between the consumer with a high load factor and the consumer with a normal load factor. There is a certain small inequity, but it is very slight compared with the inequity introduced by the kVA system of charging, under which the low-power-factor consumer has to subsidize the high-power-factor consumer. This system of charging appears to be based on the assumption that the capital costs on the whole undertaking vary inversely as the power factor, but probably in a municipal undertaking only about 30 per cent of the total capital cost of the undertaking varies with power factor. I am quite convinced that it is beyond the wit of man to devise a practical tariff which will give due weight to all the factors affecting the cost of supply, and it becomes rather a question of devising a tariff which will combine simplicity with the minimum of unfairness. The four factors which have to be taken into consideration are the maximum demand, the load factor, the power factor, and the diversity factor. Unless all these factors are allowed for, a perfectly fair tariff will not be devised. We have in Salford a tariff which endeavours to allow fairly for the first three factors, but diversity factor is the most difficult of all and is generally left alone. In the table on page 631 should not the peak load of consumer B be 1 250 kVA and the cost, at £5 per kVA, £6 250?

Mr. D. B. Hoseason: The general extension of the Hopkinson tariff on the lines suggested by Mr. Clark is undoubtedly the correct way of attacking the question of wattless kVA, but I doubt whether the suggestion to meter the actual wattless kVA-hours is sound. The running cost of supplying the wattless kVA-hours is really only a matter of that due to the extra copper loss in the transmission line and in the generating station. Taking a typical case, a consumer with a power factor of 0·9 who proceeds to improve it to 0·95 reduces the transmission loss for his particular quantity of power by about 10 per cent; but actually he reduces by 33 per cent the wattless kVA-hours which Mr. Clark proposes to meter. The quantity which it is proposed to meter in the arrangement described in the paper is not proportional to the running cost of supplying the lagging kVA. One method of dealing with this question of wattless kVA is to charge for it on some system of rebates or penalties on the power bill based on the square of the consumer's power factor and the approximate transmission losses. As a matter of fact, a good many of the supply undertakings in this country already do something of this description. The maximum-demand charge to cover the interest and depreciation on plant has been extended by the author from the original Hopkinson suggestion to a charge based upon the kVA of maximum demand. This has been criticized on the grounds that the kVA maximum demand is not a true indication of the capital cost of the generating station since there is a certain amount of expenditure on land, buildings and steam plant. Against that must be put the fact that in modern generating stations employing turbo-alternators the size of the alternator is not directly proportional to the kVA. A 12 500-kVA alternator at 0·6 power factor would be appreciably larger than a 12 500-kVA alternator at 0·8 power factor. With the old low-speed-engine type of alternator the difference was not so great. It is possible that, balancing the land, the buildings and the other charges against the electrical plant, a figure directly proportional to the kVA may result.

Mr. Dorey has dealt with the various types of apparatus for improving power factor, but he has not told us the field of application of each particular type. Any attempt to correct the power factor of a system should naturally be made at the source of the trouble, that is to say in the machines themselves. An examination will almost invariably indicate that, provided the horse-power and the speed are suitable, the cheapest proposition is to install high-power-factor rotary machines, i.e. make the motor a synchronous motor or correct its power factor with a phase-advancer. There still remains a considerable field for the static condenser in the smaller installations where there are no motors of more than approximately 50 h.p. These installations are really the particular field of application of the static condenser and in view of this it was not surprising to find a reference to a self-compensating motor which has just been put on the market in this country. What was surprising was that Mr. Dorey, with all the figures and curves before him, had not seized the opportunity of showing the exact relationship in which this motor stands with respect to the induction motor and static condenser. As a matter of fact, it is essentially a motor for continuous operation; that is to say, it is not intended for crane service. The slip-ring motor is rapidly dying out for continuous operation duties and we have then to compare this motor with a simple squirrel-cage motor. On a basis of first cost it is fairly obvious that the squirrel-cage motor must be very much cheaper; it has no slip-rings, no brushes, and a much simpler form of rotor winding is used. It is estimated that the self-compensating motor will cost between 40 and 65 per cent more than the simple squirrel-cage motor. As far as reliability is concerned there is no question which is the more robust machine. The self-compensating motor has, in addition to slip-rings, a commutator, brush gear and an additional winding on the rotor; and furthermore the slip-rings and one rotor winding operate continuously on the full line voltage. The only point where it might be claimed to have certain advantages is in regard to its power factor. It is interesting, however, to examine how much the consumer pays for this high power factor. The 17½-h.p. motor given in the paper has been taken and the consumption on a basis of the 84½ per cent efficiency

given in the curves is 15·4 kW. With a squirrel-cage motor of the high-starting-torque, high-efficiency type, the usual figures would be 90 per cent efficiency and 0·87 power factor, which give about 14·5 kW input and a difference of 900 watts. This 900 watts difference would result in about £13 difference in the annual power bill with a year of 3 500 hours and power costing 1d. per unit. Extending that to a 500-h.p. installation gives the additional cost of power per annum as about £350. One of Mr. Dorey's condensers put on to correct the power factor of the squirrel-cage motors and make it directly comparable with the self-compensating machines will cost something of the order of £750—a very much cheaper proposition than the capitalized value of the £350 per year paid in the case of the compensated machines. There is not only the cost of power to be considered, however, in modern production—continuity of service is by far the most important function. It matters very little to the manufacturer whether he gets a power-factor rebate or not when his power bill is only 1 per cent of the cost of production. What does matter is that he should keep on producing. It is impossible to have a more robust machine than the squirrel-cage motor, and it requires a considerable increase in the power bill to outweigh the advantage of this reliability. The practical problem of how to improve the power factor is naturally much more straightforward than the economic one of devising a suitable tariff. There are, however, a very large number of supply undertakings in existence which are making not the slightest attempt to deal with the problem. If the authors have succeeded in drawing the attention of such undertakings to the subject they have done well.

Mr. H. C. Lamb: Mr. Dorey's paper contains many strong statements and might lead people to imagine that most of the supply undertakings are in a worse case with regard to power factor than they really are. The fact is that many of them have a large d.c. load, and the converting plant is, in one respect, a blessing in disguise, in that it helps to keep up the power factor. On the Manchester system, for instance, the normal power factor is round about 0·9, and it never falls so low as to make it necessary to run generating plant solely because of idle current. Manchester, like most other undertakings, has recognized the need for power-factor correction, and the Manchester tariff is of Mr. Dorey's Class B type, which gives a bonus for power factor above 0·8, and a penalty for power factor below that figure. Some Manchester consumers have put in apparatus to raise their power factor, and they get a substantial bonus. I agree with Mr. Romero that the importance of power factor is exaggerated, and the statement in Mr. Dorey's paper on page 636 is misleading. He says: " The capital expenditure on supply undertakings varies considerably, and a round figure of £40 to £50 per kVA may be taken." In the first place, I do not believe that the average cost per kVA is anything like so high. Just before the sentence quoted above, he says: " . . . therefore for every £6 4s. per kVA spent on condensers the demand is reduced 1 kVA." The inference is that, for every £6 4s. spent on condensers, there is a saving in capital expenditure of £40 to £50. I am sure this is incorrect, and that the saving is only a small fraction of £40; it is, in fact, not much more than the £6 4s. which would have to be spent on condensers, namely that for the reason given by Mr. Romero, only a proportion of the plant is affected by the kVA demand. I also agree with Mr. Romero that a tariff which takes into account average power factor is the most correct one; by using two single-phase watt-hour meters the average power factor is obtained, and it is on this that the bonus and penalty clause in Manchester is based.

Mr. J. S. Peck: The possibility of improving the power factor on distribution systems is a subject that has often been discussed at these meetings, but I have always felt that no great advance would be made until the supply undertakings were prepared to recognize high power factor by bonus or to penalize low power factor by an extra tariff. One of the chief difficulties in framing a satisfactory tariff based on kVA is the securing of proper meters. So far as I know, there is no really simple and accurate kVA meter on the market. There are several meters which give approximations as to kVA but none, I think, which gives accurate results. I have recently inspected a most interesting American meter. It appears to give, and give accurately, nearly everything that can be asked for, but it is complicated and expensive. This meter (1) indicates on a chart every 15 minutes the maximum demand in kVA; (2) indicates on a chart every 15 minutes the maximum demand in kW; (3) integrates kWh; and (4) indicates at any instant the power factor of the system. This meter is probably too expensive for ordinary installations but will doubtless prove very useful for temporary installation on a customer's premises in order to determine the characteristics of his load. In framing a tariff there are so many variables which may be considered that it is almost impossible to devise a simple method which will give the proper weight to each one of them. I agree with Mr. Lamb and Mr. Romero that the importance of the wattless component is often over-stressed, for until a generating plant and cables are fully loaded the power factor of the load is of little importance. There are, however, cases where a low power factor may be very objectionable. For example, if a generator is loaded to its kVA limit and there is still excess capacity in the prime mover, it may be very desirable to improve the power factor. Also, if the drop on a particular transmission circuit is so large as to be detrimental, the cost of the installation of means for improving the power factor on the feeder may be fully justified.

In Mr. Dorey's paper there are a number of statements with which I am not in agreement. A number of these have already been criticized. With regard to the synchronous condenser it should be pointed out that this apparatus is almost indispensable in certain circumstances. On long transmission lines it is used extensively for maintaining constant voltage at the end of the line or at intermediate points on the line. A static condenser would not be suitable for this purpose, for even if it were possible to adjust its capacity by cutting out sections of the condenser it would not be able to give the lagging current required in order to prevent the voltage at the end of the system from reaching too high a value at times of light load. With regard to the

saving that had been worked out in the paper for justifying the installation of static condensers, sufficient data are not given in all cases to enable the conclusions to be checked. It has already been pointed out, however, by other speakers that the figure given for the saving of generator capacity is greatly over-stated. Considerable space is devoted to a description of the "No Lag" motor. This type of motor has been very extensively advertised in America and also on the Continent, but the indications are that it has not met with quite the hearty reception that was anticipated by its makers. A motor which must have the supply voltage carried to the stator winding by means of slip-rings, and which requires an additional winding on the rotor and a commutator, can hardly be said to be as simple as an ordinary induction motor. My personal feeling is that if a high power factor is required on an individual motor of small size it is preferable to use a squirrel-cage motor with a static condenser rather than a motor having a commutator and slip-rings.

Mr. O. Howarth: The business of electricity supply undertakings is to sell electrical energy. Success will only come if the tariff is attractive to the prospective consumer. Many people will not look at any but a perfectly straightforward tariff which they can understand with ease and which can be related to their works costs. They do not want any factor in their charge which will present difficulty; in fact, they will use some alternative to electricity rather than be bothered by tariffs based on kVA or power factor. They are prepared to pay for kWh and they might possibly be persuaded to pay for kW of demand which they can understand when related to the horse-power available, but they do not understand kVA or power factor, partly because they do not want to. There is another class of consumer who knows too much about power factor to be persuaded to pay on it. Undertakers who take a bulk supply come within this class. Of course, there must be some consumers who must have electricity at any cost, and these are the victims of the tariff dissectors. On page 638 Mr. Dorey gives figures for Bolton, Lancashire, which work out at 0·49d. per unit with coal at 20s. per ton plus a standing charge of about £3 15s. per kW per annum on the kW charge and the same on the kVA charge with a power factor of 0·75. Another tariff quoted is for a Scottish undertaking, where the price is 0·4d. per unit with coal at 20s. per ton plus £10 per kW per annum for a 250-kW consumer. I am well aware of the strong objection of the Lancashire manufacturer to paying a kW charge which he regards as money paid for nothing when he is on short time, but I was always under the impression that the same thing applied to Scotland. At 30 per cent load factor the Scottish price works out at 1·31d. per unit and the Bolton price 0·83d. per unit with coal at 20s. Can the authors assure us that these differences in price actually obtain between ordinary power consumers in the different districts? Owing to the competition of oil and steam plant, most undertakers have to sell electrical energy at what they can get and not at what they would like to sell. If we have two consumers, A being situated ¼ mile from the power station and taking 100 kW at 0·5 power factor, whilst B is situated 10 miles away and takes 100 kW at unity power factor, it will obviously cost more to supply B than A, but the authors suggest that A should be made to pay more than B. The distance from the power station has to be averaged out and with the ordinary power consumer who uses a number of motors of various ratings up to about 100 h.p. the power factor should be averaged out also. Consumers have adopted the electric drive because they can sectionalize their shafting or have an individual drive for small machines if they wish. A power factor charge to them simply means that they must install additional apparatus. If 500 kW is required on one machine a consumer might with advantage be induced to install a synchronous machine and get a good power factor. It might be worth while, especially if he has to be supplied by a long transmission line, to offer him special terms for a high power factor, but he is not an ordinary consumer. The ordinary consumer likes to have some simple piece of apparatus and does not want to be bothered with complications. The induction motor appeals to these consumers because of its simplicity. I have calculated the saving that would be effected if consumers improved their power factor, and even with consumers several miles from the power station the saving was much less than that shown in Mr. Dorey's paper. The greatest saving would be effected by reducing the transformer capacity in the consumer's substation, but it is doubtful whether it is safe to do this as there is always the possibility of the consumer running without his condensers due to breakdown or mistake, in which case the transformers may be damaged. If any saving is to be effected by improvement of power factor the supply undertakings can install condensers and pocket all the saving, with the advantage that the condensers will be under their control and can be switched on and off to suit them; they will then derive full benefit from their use.

The chief objection to these tariffs is the impossibility of obtaining satisfactory metering. Many of these tariffs are framed in such a way that it is quite impossible to meter, and a compromise has to be arranged with the consumer. We can only define the kVA and power factor on a three-phase, 3-wire load by assuming symmetrical voltages, and our experience of the inaccuracies of meters which depend for their accuracy on symmetrical currents and voltages should warn us off these assumptions. We cannot measure what we cannot define. The meter artifice suggested by Mr. Clark is most unsatisfactory because the consumer may at any time ask "What *does* this meter measure," and what answer can be given? The Aron kVA meter mentioned in Mr. Dorey's paper is undoubtedly the best piece of apparatus on the market at the present time for measuring kVA. It indicates the kVA demand on the Merz system but, as he points out, it will not register kVA-hours. If it will not register kVA-hours it is obvious that it cannot accurately integrate the kVA over a period and indicate the average kVA during that period as it is required to do to work on the Merz principle. It measures the kVA if the load is approximately constant, and might be expected to give results within about 5 per cent of what the true value would be if we could define the true value. Meter manufacturers have

not yet seriously tackled the problem of making a satisfactory kW indicator. When the accuracy guarantee figures are analysed we find that the meters are only guaranteed to within 4 or 5 per cent at working loads. Let the manufacturers supply a satisfactory kW demand indicator before they go on to more complicated measurements. If an undertaking installs complicated meters which only approximate the quantities to be measured specifically, and that undertaking is challenged on the accuracy of its metering, what is it to do? It will have to come to terms. For this reason I think that these systems of charging should be avoided as far as possible.

Mr. E. P. Hill: In the summary, Mr. Dorey states that his paper gives a description of the modern static condenser and also of types of power-factor-rectifying plant that have been developed during the past three years. I find that the principal types with which he has dealt embody the principles of Leblanc (1895 patent), Scherbius (Brown-Boveri) 1912, and Miles Walker 1912, and he does not bring forward new types of power-factor-rectifying plant. Fig. 4 appears to be identical with the one given in an article * on "Phase Compensation" by Mr. T. Ellis of the A.E.G., but such methods cannot be said to have been developed during the past three years. Mr. Dorey sets out the advantages of the static condenser, and certain serious limitations have also been mentioned. One of the main disadvantages appears to be that the economical voltage is 600 volts, and that the size and cost are inversely proportional to the square of the voltage; so that at 440 volts without the auto-transformer the size of the condenser is almost double that at 600 volts. The author states that the cost of 600-volt units in series for use on 3 000 volts is approximately the same as for 600-volt working. The use of high-tension condensers is not encouraged. Is this not due to the reduced reliability at 3 000 volts which entails that in order to manufacture a reliable article the condenser is not then an economical proposition? This is of importance in many cases where the bulk of the motors are running at voltages from 2 000 to 6 600. It would be interesting to know if the condenser mentioned as being run across 3 000 volts for the purpose of test and experience was of standard construction, or whether it embodied any special features. As both the size and cost of the condenser vary inversely as the frequency, it follows that at 25 periods the economical advantages are much less, for at the price of £6 4s. per kVA other forms of phase compensation would often be preferable. Mr. Dorey states on page 636 that the static condenser is a very flexible apparatus. On the contrary, in some respects they are far less flexible than other forms of power-factor correctors, for the reason that, unless considerable cost is incurred, the amount of leading current cannot be varied with load, and this may at times be a disadvantage to a consumer. In spite of the relatively few accidents which have occurred with transformers immersed in oil, there is in some quarters a disinclination to install further apparatus in which quantities of inflammable oil are used as a cooling medium, and possibly in situations involving serious consequences in case of fire. The possibility of moisture gradually affecting the insulating quality of the thin dielectric used, is no doubt one of the reasons for the anxiety of the makers to avoid the manufacture of condensers for higher voltages than 600 volts, due to the relatively small factor of safety. Whereas in the case of a transformer, for example, the insulation and clearances can be made very ample, to ensure that breakdowns from such causes are extremely rare, in the case of a static condenser the matter is more difficult as the output is inversely proportional to the thickness of the dielectric. To sum up, it would appear, therefore, that with low frequency (i.e. where the magnetizing currents of transformers are high) the condensers are economically least suitable. On voltages higher than 600 they may become dangerous unless expensive. Below 600 volts they are apparently uneconomical unless an auto-transformer is adopted, and consequently the field of useful service is limited. If there is a d.c. load to be supplied in addition to the a.c. motor load, it is often more suitable to install a rotary converter at the substation. Earlier in the discussion Mr. Lamb mentioned the beneficial effect of rotary-converter load upon the power factor of the Manchester Corporation supply. In Dr. Kapp's paper Mr. Chattock also stated * that in Birmingham the power factor is improved from 0·66 to 0·79 by adding approximately 14 500 kW of rotary plant. The total load then was 58 000 kVA. Mr. Chattock assumed that the rotary converter was running at unity power factor. If running at 0·98 this would give a total power factor of over 0·8. A normal rotary converter is capable of running with a reasonable amount of leading wattless component without fear of serious overheating. As it is readily possible to change the transformer tapping by a h.t. tapping switch to obtain the desired leading wattless current even with wide variations of d.c. voltage (such as in the case of a converter running at 440 volts for lighting and 550 volts for traction), the rotary converter has advantages over the motor converter in this respect. The power factor of all static rectifier plant is, of course, relatively worse than that of a rotary converter, and such plant is at a disadvantage in this respect.

Mr. W. Fennell: The question of power-factor tariff is of secondary importance perhaps to those who sell in bulk to smaller undertakings, but it is of primary importance to those undertakers who have to buy power in bulk. Whilst the objection which is made to tariffs based on kVA or to charges for wattless component—viz. that they are not understood—does not apply with so much force to one undertaking selling to another, as there are electrical engineers on both sides, there is a risk of the "bulk consumer" being charged too heavily by reason of abnormal conditions, such as mains faults, etc. From that point of view it is unfortunate that so little has been said of what is being done in arriving at the power factor for bulk supply tariffs. An account of the actual arrangements made as to power factor by large undertakings selling in bulk would be interesting. With regard to tariffs for ordinary power consumers, I think it is about 5 years since I said on the occasion of a paper on "Tariffs" at Manchester something to the effect that the wise power station engineer, if in any

* *Electrician*, 1925, vol. 94, p. 590.

* *Journal I.E.E.*, 1923, vol. 61, p. 100.

case he found the tariff did not fit an important intending consumer, would not hesitate to make a new one for the occasion. The tariffs for which I have been responsible have always had a saving clause that we may sell power "by agreement." The important thing is to secure all the paying business. In cases where the maximum demand either in kW or power factor is proposed to be taken into account as an act of justice, I am of the opinion that it is of primary importance that the time of maximum demand should be considered. The question arises: Is the maximum recorded figure to be taken as a basis if it occurred in the morning in mid-summer, or is it to be taken during the time of peak load on the feeder or of the generating station concerned? A consideration of the basis of cost of generation and distribution shows that it is unscientific and unfair to fix a tariff based on maximum demand without having some scheme for determining the time of maximum demand and of ignoring or reducing the chargeable demand to a reasonable extent if it occurs at unimportant times. I have recently been engaged in negotiating a bulk supply agreement where the recorded maximum kVA is multiplied by a constant of 0·5 in summer, increasing gradually to unity in December. That is a reasonable differentiation between months but we should in justice go further. The chargeable kVA which matters and which should be chargeable is that usually existing during the late hours of the winter afternoon. Where a bulk supply is involved it is well worth while to have a recording ammeter and voltmeter and to use the valuable information so obtained as the basis for obtaining the chargeable kVA instead of using maximum-demand meters. These latter sometimes indicate readings which no one can account for and which may be due to accidental or transient excess demand or low power factor which in no way benefited the bulk consumer or caused the supplier any extra expense commensurate with the extra charge made because of it. Having those two curves—amperes and volts—the supply engineer may, for instance, ignore a certain large kVA which occurred at a time of light load on the generators, and take into account only the usual sustained kVA at times of peak load on the power station or feeder. It is not suggested that recorders should be fixed in every factory. The ordinary consumer wants a simple and definite meter system, and if discretion is exercised in its use a kVA meter will not cause any friction with the consumer who agrees to be charged on that basis.

(*Communicated*): There is one important point which the papers do not emphasize in dealing with power-factor-correcting devices. It is a common fallacy to imagine that the installation of, say, a rotary converter or special motor running at nearly unity power factor will compensate for low power factor on a system because the power-factor indicator reading improves. There is just the same loss due to wattless component as before, and this can only be corrected by installing apparatus with considerable and controllable leading power factor. For this reason the need for considering synchronous motor-generators or condensers is just as important where there are converting substations as in these cases where the system is entirely alternating current; sepecially as the ratio of a.c. to d.c. loads is likely to increase in almost every case as the area is developed.

Mr. L. H. A. Carr: Since Mr. Dorey's paper is apparently a résumé of the various types of apparatus used for power-factor correction, one feels that he has rather cursorily dismissed the synchronous and synchronous-induction motors. Whilst the salient-pole synchronous motor has been installed in large numbers during the past 15 or 20 years, it should be emphasized that the use of the synchronous induction motor has increased enormously during the past 4 or 5 years, and, judging by the number manufactured in this country, it would appear that the synchronous induction motor is at the present time the most popular type of machine for power-factor correction, a position that it probably deserves. It is unfortunate that Mr. Dorey, when dealing with compensated induction motors, should describe at such length only one proprietary type out of many, and also that he should refer to it as a "comparatively new type" although it was known, and manufactured, some 25 years ago. Compensated induction motors may be divided into two main classes. The first class is that in which power is led to the brushes at line frequency, the rotor being similar to an ordinary d.c. armature. This motor is frequently known as the polyphase shunt, or polyphase series motor, according to its connections, and was first described by Wilson in 1888. Later, about 1901, it was developed by Görges, Heyland, and Latour, and was commercially manufactured by the A.E.G. and Siemens and Halske, but failed to find a market. In recent years it has been re-introduced by several of the Continental firms. In the second type the primary winding is normally on the rotor. A small tertiary winding, or a series of tappings on the primary winding, is connected to a commutator, and the brushes pick off power at slip frequency only, and this power is fed into the stationary secondary winding. This motor was described by Osnos in 1902 in almost all its possible modifications. It is now, with minor variations, manufactured by several firms, principally on the Continent. When discussing polyphase machines with commutators, it must be remembered that the a.c. commutator has always one great disadvantage compared with the d.c. commutator. In the d.c. machine the current is collected from a point on the commutator where the value of the E.M.F. between adjacent commutator bars is zero. On the polyphase a.c. machine the flux rotates relatively to the brushes, and, no matter how low the periodicity, at some period of time each brush collects current from a part of the commutator where the voltage between adjacent commutator parts is a maximum for the machine. For this reason a.c. commutators are larger, and necessitate higher losses, than the corresponding d.c. commutators. A further type of power-factor-correcting motor not mentioned by Mr. Dorey is the self-excited synchronous induction motor, first described by Fynn in 1906, and now manufactured in small sizes both on the Continent and in America. Yet a fourth type is the Torda motor (1923) which really consists of an induction motor with a phase-advancer winding wound on the same core or cores as the main winding, but with a different number of poles so that the two sets of windings and fluxes

operate independently. All these types suffer from the same economic defects. Compared with the induction motor they are expensive in first cost, due to their extra complications, and low in efficiency. Where power-factor correction is required it is cheaper, both in first cost and in running charges, to install in the smaller sizes, say up to 60 h.p., a plain induction motor with static condensers, and above that to utilize either the salient-pole synchronous motor, or the synchronous induction motor, the exact choice depending on the starting torque required.

[Mr. Dorey's reply to this discussion will be found on page 652. Mr. Clark's reply will be published later.]

South Midland Centre, at Birmingham, 31 March, 1926.

Mr. J. Hargrove: Mr. Lawson suggested that there was no incentive for supply undertakings to adopt a power factor tariff unless its cost to them proved less than that of increasing the size of their generating plant, but it appears to me that this entirely overlooks facts which were made clear in the Weir Committee's report, namely, that whereas the average capital cost of the generating plant is £23·8 per kW, that of distribution is £28·5. It is clear from this that the increased cost of cables, etc., necessitated by low power factor is at least equal to the increased cost of generating plant, and that therefore equal attention should be given to it. It was also suggested by Mr. Lawson that a reduction in rates was in the nature of a gift to the consumer, and his remarks tended to strengthen the impression one had that supply undertakings in general did their utmost to maintain their charges at the highest possible figure. This would appear to be quite a wrong attitude to adopt, as a curve supplied by Mr. Kennedy and incorporated in the Weir report tends to show. This curve shows that whereas at 2d. per unit 110 units per head are used, if the price is reduced to 1d. the consumption rises to 500 units per head. This fact is well worth consideration, as increased consumption naturally tends to reduce both capital and operating costs per kWh. Turning to the question of tariff, it is not at all clear why Mr. Clark should have taken 0·8 power factor as his basis, whereas Mr. Dorey adopted 0·75. I have had experience of a tariff which might be described as a modification of the three-part tariff referred to by Mr. Dorey. The price in this case is based on unity power factor, and is fixed by a sliding scale according to horse-power (or kVA) of plant installed. A sine meter is used in addition to the kilowatt meter, and the units registered by it are charged at a definite fraction ($\frac{1}{8}$) of the price per unit of power. A minimum consumption has to be guaranteed by the consumer, amounting in this case to an average load of 40 per cent of the capacity installed, for 611 hours per quarter (47 hours per week). In case the consumption in any one quarter does not reach this amount, the charge is based on this minimum, but a rebate of 30 per cent is allowed on the units contracted for but not taken. It will be seen that this is, in effect, very similar to the three-part tariff, but does not require a maximum-demand indicator. Fig. A clearly demonstrates the effect of a tariff such as this, at various power factors, and it will be seen that between 0·9 and 0·6 power factor the curve is practically a straight line, but that it rises very rapidly below 0·6. It seems obvious that a tariff such as this, by which a definite extra charge is made, proportional to the extra kVA, is more equitable than the one in which the extra is inversely proportional to the power factor, as the extra cost of generation and distribution are very nearly in direct proportion to the extra kVA required. Any consumer entering into an agreement to take a supply on any such terms as the above should give very careful consideration to the balance of capital charges, for plant to give a high power factor against the extra cost of current at a lower power factor. In this respect it may be taken that to be a paying proposition the yearly saving due to improved power factor must be at least equal to one-fifth of the extra capital cost involved.

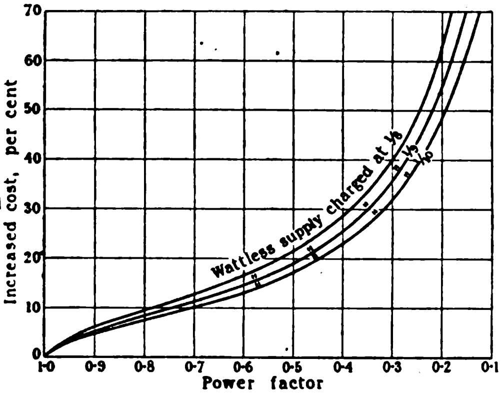

FIG. A.—Curve showing increased cost per kWh at various power factors.

Basis of charge: x pence per kWh + cx pence per kVA-hour of wattless supply, where $c = \frac{1}{8}, \frac{1}{5}$ or $\frac{1}{10}$.

Mr. W. P. Conly: I should like to ask Mr. Dorey's opinion as to the best method of obtaining the desired pressure of 600 volts across the condenser of a power-factor-correcting equipment. In his paper Mr. Dorey advocates two alternatives: (1) To overwind the secondary of the main transformer to carry the wattless component at a line voltage of 600, and (2) to provide an auxiliary auto-transformer stepping up the wattless component from the normal line pressure to 600 volts. In an actual case under my notice it is required to install a 250-kVA transformer at 5 000/440 volts, three-phase, 25 cycles, and at the same time to raise the power factor from 0·7 to 0·92. The former method of the overwound transformer shows a financial advantage of approximately £31. Is this sufficient, in Mr. Dorey's opinion, to justify its use?

Mr. J. Young: I am chiefly interested in this question of power-factor improvement in connection

with small fans taking from 50 to 150 watts. The standard practice with these fans is to fit a small condenser with each either on the down rod of a ceiling fan, or combined with the fan regulator. These condensers have a capacity of from 4 to 12 μF, and I should like to ask Mr. Dorey whether in his opinion there is any loss in capacity either if kept in stock or in use. I have made a large number of tests during the past 6 months on these small condensers. Although this time is not long enough to enable any definite opinion to be formed, I have obtained what appear to be rather curious results. I have several times been unable to obtain the same power-factor correction with a condenser after it has been in use or kept for some time. Quite recently I had a very unfortunate instance of this. A fan and a condenser were connected up and gave a power factor of 0·97, the power factor of the fan being 0·61. The fan was then run for some time, being switched off at night, and on repeating the tests next morning for an inspector I could only obtain a power factor of 0·93. Is there any reason for these results ? I do not suggest that the trouble is all due to the condenser; it may be that the connections are at fault, or that the insulation has deteriorated after standing overnight. Is there any simple way of testing the condensers ?

Dr. R. G. Jakeman: A case came to my notice recently in which a condenser and transformer were used for correcting an induction-motor load. It was found that if the condenser was switched on when the motors were out of circuit, a current of about 3 times the normal was taken, which, however, rapidly fell to normal. If, however, the motors were in circuit first, only normal current was taken. I should be glad if Mr. Dorey would give an explanation of this. It appears to me that the ideal method of power-factor correction is to supply a separate condenser for each induction motor, so that the condenser is switched on and off with the motor and the stator winding acts as a discharge resistance. The objection appears to be the cost, but since the method is applied very largely to fans it does not seem unreasonable that it should be extended to larger motors. This method leads to a new tariff system. The condensers could be supplied and maintained by the supply undertaking, remaining their property. The consumer would pay for the energy used and would have a rebate for allowing the supply undertaking to fit the condensers. The power factor could be corrected to any desired figure, without the consumer being required to understand anything about it. The "No Lag" motor mentioned by Mr. Dorey and described in the *Journal* 10 years ago has the great disadvantage that the primary is wound on the rotor, so that the main current has to pass through the slip-rings. The firm with which I am connected has developed a form of compensated motor which has not this disadvantage.

Mr. F. C. Hall: In regard to Mr. Dorey's paper, it is true that both synchronous and auto-synchronous machinery has been previously described in the *Journal* and both classes are serving many useful purposes; I therefore feel that the author has somewhat given this side of the subject the "cold shoulder"—more especially as he singles out the rotary condenser and proceeds to compare it with the static condenser, to the disadvantage of the former. Supply undertakings abroad appear to use rotary condensers to a larger extent than is the case in Great Britain, and they use them in the form of very big units, certainly up to a capacity of 15 000 kVA, despite the fact that this is a less efficient way to make use of the machine. The greatest value can be got out of synchronous machines when they are used both to deliver load and to correct the power factor; and whilst it is not economical to adopt them in all cases, there are certainly many occasions when it is better to use them than any other method for improving the power factor. An important feature about synchronous and auto-synchronous machines is, that, providing they are delivering a fairly high percentage of kW load in proportion to their kVA capacity, they occupy considerably less space than static condensers and the necessary auto-transformers and switchgear for the same, with consequent reduction in capital cost of buildings, floor-space, etc. Furthermore, in these conditions the efficiency—by comparison with the ordinary induction motor or motors which would otherwise be required to deliver the load—is only about 1 per cent lower than that for the latter machines. The author's treatment of the subject of charging consumers of varying power factors brings out many interesting points, and shows clearly that whilst some supply undertakings offer fair and reasonable tariffs, others either offer no inducement whatever or make no discrimination between the biggest offenders and those who only offend in a small degree.

I find myself at variance with Mr. Clark's revolutionary idea to regard low power factor as a useful source of profit. It seems to me that as power factor is linked up with the question of the general efficient running of a system, we, as engineers, should extend our influence towards the improvement of the power factor, rather than accept something which is bad and endeavour to make money out of it. With regard to Mr. Clark's interesting suggestions as to the more complicated methods of charging for electricity, this may be satisfactory in certain cases of large consumers, but the cost of metering equipment is already high in the case of the great army of small consumers, and it seems desirable for supply undertakings to evolve in their case a tariff which is as simple as possible.

Mr. E. W. Dorey (*in reply*): Several of the speakers have suggested that I should have taken the opportunity of making comparisons between the static condenser and other types of plant for power-factor correction, but as each case needs special and individual consideration it is well-nigh impossible to give comparative figures that would be of any real use. A comparison between the cost and efficiency of an auto-synchronous motor of a given output and those of an induction motor of the same output working with a static condenser, does not really give much useful information. The static condenser is essentially an equipment for correcting the power factor of the load as a whole and not

the power factor of individual machines. The auto-synchronous motor and also the static condenser have each its special field of application. When dealing with a load comprising a number of comparatively small motors, the static condenser is almost invariably the best solution.

In considering the use of auto-synchronous motors installed for the power-factor correction of the total load, an important item to be borne in mind is the output of the auto-synchronous motor. There are cases where an auto-synchronous motor has been installed to work at about one-fourth or one-fifth of its full-load output and, consequently, at low efficiency, as the machine had to be so designed as to be able to give the equivalent kVA output required for power-factor correction. Efficiency in such cases is an important factor that should not be overlooked. On the other hand, where auto-synchronous motors of, say, 100 h.p. upwards can be utilized working at three-quarters to full load, they undoubtedly have a good field of application. The auto-synchronous motor certainly has the advantage of ease of regulation of condenser capacity. In the case of a static condenser it is quite a simple matter to arrange that the capacity can be varied to give one-third, two-thirds or full output.

If we take the case of an auto-synchronous motor of, say, 200 h.p. working in conjunction with 200 h.p. of small induction motors, the installation being designed to give a power factor of, say, 97 per cent lagging, the auto-synchronous motor will be excited in such a way as to ensure that the required degree of correction is obtained at maximum load, and will normally remain so set during the whole of the day; the capacity component will therefore, for all practical purposes, remain as fixed as with a static condenser. With a kVA-demand tariff it may not always be safe to correct to unity power factor, as there is always the danger that at the time of maximum demand the load may be less than anticipated and cause a leading power factor, with a penalty similar to that for the equivalent amount of lag. It would undoubtedly be an advantage in most cases if a minority of the consumers of a supply undertaking had a power factor of unity or a leading power factor; but, as time advances, the majority of the consumers may have corrected their power factors, and when the majority are working with unity or leading power factor the conditions on the system may be very objectionable to the supply undertaking and interfere seriously with the voltage regulation. Looking to the future, therefore, it would seem that the most desirable course is to impose a tariff which will not encourage consumers to run with a leading power factor. A lagging power factor of about 95 per cent should in the majority of cases be quite satisfactory both to consumers and to supply undertakings.

My reference to rotary condensers was confined to conditions obtaining in Great Britain where the field of application is very limited. Abroad, the rotary condenser, as referred to by speakers, frequently has to operate with lagging instead of leading power factor. I do not agree with Mr. Hart that on a 25-cycle circuit in Great Britain the rotary condenser is a better proposition than the static condenser, because, if the losses are taken into consideration, the static condenser will undoubtedly have the advantage, although its capital cost will almost invariably be higher.

The President and other speakers have referred to the necessity of switching static condensers off with the load, in order to avoid voltage-rise, and in the majority of cases this is a very necessary precaution. In the case of static condensers installed by the consumer, the condenser is almost invariably switched off with the load. On the other hand, if the condenser is installed by the supply undertaking at, say, an unattended sub-station, some means would have to be devised for automatically disconnecting it as the load falls off, and switching it in again when the load comes on. So far, I know of no cases where this method has been adopted. The tendency nowadays, and rightly so, is for the consumer to be encouraged to install the condensers or other corrective plant, and he may usually be relied upon to switch them out when the load goes off.

Mr. Hart says that there is divided opinion as to whether the supply undertaking or the consumer should be responsible for the improvement of power factor. There may certainly be a difference of opinion, but I suggest that the great majority of engineers are agreed that it is the consumer who is responsible for the low power factor of the load and who should be encouraged and enabled by the provision of suitable apparatus to install plant for power-factor correction. If the supply undertaking itself endeavours to correct the power factor, the difficulty of capacity regulation immediately arises.

There is one interesting case of an important supply undertaking in Great Britain with a day load of about 16 000 kVA at a lagging power factor of 0·50 which is obliged to improve the power factor of the load before linking up with another supply undertaking. A power-factor tariff has not been adopted and it is now found to be quite impossible to effect the correction on the distribution system. The installing of expensive and inefficient rotary condensers at the power station has been considered. Under such conditions the distribution system will still have to operate with double the current and four times the losses which would occur under equivalent conditions with unity power factor. This is the ultimate fate that will await many supply undertakings who neglect the power-factor problem, and with the rapid increase in the number of linking-up schemes it is not surprising that the majority of supply undertakings are now adopting some form of tariff to compel consumers to improve the power factor of their loads.

In reply to the President's remarks regarding voltage regulation with condensers connected direct across transformers of the pole type, I have no definite data as to the installation referred to in the paper, but the remarks of the engineer, that the voltage regulation is improved, are significant. It is important in an installation of this kind to divide the capacity into a large number of small units distributed as widely as possible over the system; and, quite apart from the other advantages which accrue from the installation of condensers in this way, it should, if properly designed, considerably improve the voltage regulation.

Mr. Ellis has referred to the "Maxigraph." This is an instrument of great merit in special cases such as those mentioned, or for special power-factor or kVA-demand tests, but as an ordinary commercial instrument for metering the kVA demand it is unnecessarily elaborate and costly.

Mr. Kapp and Mr. Young have referred to the use of small individual condensers in conjunction with fans. These have now been developed for commercial purposes, the condenser being fixed in the regulator housing. Small alternating-current fans have a notoriously bad power factor, about 60 per cent, so that if a direct-current fan load is being changed over to alternating current the current will increase by something like 60 to 70 per cent at the same voltage, and the introduction of a condenser in an a.c. fan to bring the power factor up to 91 per cent will keep the current increase down to about 10 per cent. Mr. Young refers to the variation in the capacity value of a fan condenser, but the case he instances must be quite an abnormal one, as in the ordinary way the variation of capacity over many years should be quite negligible.

In reply to Mr. Hill, the 3 000-volt outdoor condenser to which reference has been made in the paper was quite a standard product. Mr. Hill regards the voltage of 600 on a condenser as a disadvantage, but it does not seem to be more of a disadvantage than to use, say, a 33 000-volt transmission where it would be possible at considerably greater cost to use 11 000-volt transmission. It is a question entirely of the most economical plant for the job.

In reply to Mr. Carr, I would point out that in my short paper it was impossible to refer more than briefly to certain types of plant for power-factor correction, and to touch only the fringe of the subject.

Coming to the question of tariffs, it is pleasing to hear that Mr. Chattock and Mr. Lamb have instituted at Birmingham and Manchester respectively a power-factor-rebate tariff for a.c. consumers, despite the fact that in both towns they are in a relatively good position from the point of view of power factor. This, in itself, seems justification for the extended application of a power-factor tariff, particularly in the case of undertakings mainly operating with industrial a.c. loads.

In reply to Mr. Lamb, it was not my intention to suggest that for every £6 4s. spent on 50-cycle static condensers there would be a saving of from £40 to £50 in the capital outlay of the undertaking. In the £40 to £50 figure are items amounting to possibly half, or more, quite unaffected by power factor, but my intention was to convey that only £6 4s. per kVA on a 50-cycle undertaking is necessary in order to justify the installation of a condenser, and there must be ample margin between this and the actual capital cost per kVA of such portion of the undertaking as is affected by power factor. In the case of Manchester with its favourable power-factor conditions, the saving may be only a small fraction of the £40 to £50, but it is nevertheless sufficient to justify the offering of quite a substantial power-factor bonus, and I suggest that in the majority of supply undertakings it will be quite a large fraction, possibly 50 per cent or more.

Mr. Howarth suggests that as the distance factor has to be averaged out amongst consumers of a supply undertaking, so should also the power factor be averaged. This does not, however, seem to be logical, as, whilst the consumers have little or no control over the distance factor, they certainly can control the power factor, and the tariffs should give them some opportunity of realizing their responsibility in this respect.

I disagree with those speakers who say that there are not satisfactory meters for putting into effect the power-factor tariff, and that it is not possible to apply such tariffs to small consumers. The North Metropolitan Electric Power Supply Co. has instituted, with every success, a power-factor tariff applying to almost all classes of industrial consumers from the largest to the smallest, in most cases on a kVA-demand basis using the thermal demand indicator and the Hill-Shotter kVA-demand instrument.

In preparing a tariff based on kW demand, some basic power factor must be assumed, and it follows that the loads with power factors above the basic figure must pay for those below it. Is it not therefore quite logical and reasonable to put the tariff on a kVA-demand basis worked out on the basic power factor, and let those consumers below the basic figure be penalized and those above get a bonus? In some cases a two-part tariff—a kW demand and a running charge per unit—provides for varying the charges with the average power factor, but it would surely be a much simpler and more straightforward tariff to alter the kW charge to a kVA charge and leave the running charge entirely unaffected by power factor. The metering would be much simpler.

The whole problem of power factor is linked up essentially with that portion of the tariff charges attributable to so-called fixed charges, the tendency nowadays being to include in the fixed-charge portion of the rates many items that were previously included in the running charge per unit, which has been referred to by Mr. Kapp. The fixed charge or equivalent part of the rate is, I contend, the only portion that should be affected by power factor, and it is difficult to see what justification there is for offering for an improvement of power factor a bonus on the running charge per unit, other than a small fraction due to a reduction in the losses in transmission, which I suggest can quite adequately be taken care of in the fixed-charge portion of the rate.

REPORT OF THE COUNCIL FOR THE YEAR 1925–1926, PRESENTED AT THE ANNUAL GENERAL MEETING OF 27 MAY, 1926.

CONTENTS.

REPORT.

The Council, at the Fifty-fourth Annual General Meeting of the Institution of Electrical Engineers, present to the members their Report for the year 1925–26, covering approximately the period from 1st April, 1925, to 31st March, 1926, and take this opportunity to thank the many members who have so willingly contributed to the Institution's continued progress and prosperity.

(1) Membership of the Institution.

The changes in the membership since the 1st April 1925, are shown in a table given in Appendix A.

The following table shows the growth of membership for the last 10 years :—

Year	Membership	Increase or decrease
1917	6 613	— 63
1918	6 667	+ 54
1919	7 023	+ 356
1920	8 146	+ 1 123
1921	9 449	+ 1 303
1922	10 275	+ 826
1923	10 911	+ 636
1924	11 415	+ 504
1925	11 743	+ 328
1926	12 142	+ 399

As might have been expected, the high rate of increase of membership which followed the war period has gradually come down to a more normal, but still very satisfactory, figure.

(2) Examinations.

The Associate Membership Examination was held in April and October, 1925, in London, Birmingham, Cardiff, Glasgow, Manchester, Newcastle-on-Tyne, Plymouth and Southampton, and also in Australia, Ceylon, India, New Zealand, South Africa and the U.S.A.

A certain number of candidates submitted theses and papers during the year in lieu of the Examination.

(3) Honorary Members.

The Council have pleasure in recording that, as announced at the Ordinary Meeting held on the 5th November, 1925, they have elected Dr. S. Z. de Ferranti, D.Sc., to be an Honorary Member of the Institution.

Dr. Ferranti, who became a Member of the Institution in 1891, was President in 1910 and 1911, and was awarded the Faraday Medal in 1924.

There are now 11 Honorary Members.

(4) Local Honorary Secretary for New Zealand.

The Council have appointed Mr. A. Gibbs, Deputy Chief Engineer of Telegraphs, Wellington, to be Local Honorary Secretary of the Institution for New Zealand, in place of Mr. J. Orchiston, resigned, who had held that office since 1911.

The Council cordially thank Mr. Orchiston for his valuable services over a long period of years.

(5) Faraday Medal.

The fifth award of the Faraday Medal has been made by the Council to Colonel R. E. B. Crompton, C.B., Honorary Member and Past-President of the Institution.

(6) Deaths.

The Council regret to have to record the death of the following 67 members of the Institution during the year :—

Members.

Arnot, W.
Barrett, Sir William F., F.R.S.
Beresford, Colonel C. F. C., R.E.
Bevis, H.
Bradwell, J. D. L.
Cooke, C. W.
Cooper, W. R., M.A., B.Sc.
Corlett, G. S.
Crapper, Professor E. H.
Gray, Prof. A., M.A., LL.D., F.R.S.
Gray, J. Hunter, K.C.
Hillairet, A.
Hird, F.
Jacob, A.
Lundberg, A. P.
Maclean, A. B.
Matthews, H. B.
Mills, A. E., M.A.
Munro, J. M. M.
Myers, E. R.
Pigg, J.
Roberts, M. F.
Salomons, Sir David, Bart., M.A.
Sankey, Captain H. R., C.B., C.B.E., R.E.
Stevenson, G.
Tate, L. G.
Williams, H. L., B.A.
Wise, G. M.
Wyllie, A.

Associate Members.

Angus, J.
Baeza, E. A.
Bailie, J. D.
Billington, J. R.
Chambers, G.
Coates, H. J.
Fruhe-Sutcliffe, Major R.
Giffen, A. E.
Gundry, W. E.
Ingleby, J. C. B.
Jennings, E. J.
Kinsey, A. T.
McKie, J. W. L.
Mills, H. R.
Milnes, W. M.
Minton, R. C., B.Sc.
Moinet, J. V.
Shepherd, G. M. B.
Smith, P. H. F.
Stickland, H. M.
Sutton, G.
Tweedy, G. K.
Wild, A. G.

Graduates.

Blake, G. T.
Colson, G. B.
Hudson, W. J.

Students.

Adbutharaj, R.
Anson, H. St. G.
Bobby, G. E.
Bowers, W. E. H.
Cook, A. E.
Dawbarn, D. I.
Ferens, L.
Harding, E. H.
Harries, D. G.
Karkaria, A. J.

Associates.

Devey, A. C.
Wickenden, A. H.

(7) Institution Building.

Considerable use has again been made of the Lecture Theatre and meeting rooms by allied scientific and technical societies, and the Council have been glad to learn that the hospitality extended by the Institution in this manner is much appreciated by the bodies concerned.

(8) Meetings.

During the past twelve months 374 meetings have been held in London and the Local Centres by the members, the Council and the various Committees. A detailed statement is given in Appendix B.

The Premiums awarded by the Council for papers will be announced about the time of the Annual General Meeting.*

(9) Local Centres and Sub-Centres.

The interest in, and attendance at, the meetings of the Local Centres and Sub-Centres have been well maintained.

The President has attended annual dinners, meetings, or other functions at the Centres at Birmingham, Glasgow, Leeds, Liverpool, Manchester and Newcastle, and at the Sheffield Sub-Centre.

On each occasion, the President addressed the members and was much impressed by the activities of these branches of the Institution and by their inestimable value in contributing to its prestige and extending its influence.

(10) Wireless Section.

Eight meetings have been held, at which nine papers were read and discussed.

In view of the suggested formation of a separate wireless society, a proposal which was based on a serious misconception of the aims and activities of the Wireless Section, the Committee considered it desirable, in August 1925, to publish in the Press a statement strongly deprecating the formation of a new society. Out of a discussion on the subject which took place in the Press, several valuable suggestions emerged. These were carefully considered by the Committee of the Section, and as a result the following Report was presented to, and approved by, the Council with a view to developing and extending the activities of the Section :

Report of Committee of Wireless Section.

The Committee of the Wireless Section have further carefully considered the proposal for a new Institute of Wireless Engineers and are definitely of the opinion that the interests of qualified professional wireless engineers can best be served by the Institution of Electrical Engineers.

It has already been explained that an engineer with adequate wireless qualifications can become a Corporate Member of the Institution, and that other wireless engineers not reaching that standard are eligible as Graduates and, as such, can attend all meetings of the Wireless Section as well as those of the Institution.

The Committee have taken into consideration the suggestions arising out of the previous correspondence

* See "Institution Notes," page 717.

on this subject which appeared in the Press, and with a view to improving and extending the activities of the Wireless Section and making it more definitely representative of professional wireless engineers, put forward the following recommendations :—

(1) While it is essential that the standard of qualifications for membership of the Institution should be maintained, more opportunity should be afforded to the physicist engaged in wireless work to become a member of the Institution. Applications for membership of the Institution based upon the usual general scientific training and wireless professional qualifications should be referred by the Secretary to a Wireless Section Membership Sub-Committee, which will make reports and recommendations for the guidance of the Membership Committee of the Council.

(2) The qualifications for membership of the Wireless Section should remain as at present, viz. "that he is a member of the Institution and is actively engaged in the study, design, manufacture, or operation of wireless or high-frequency engineering apparatus;" and the Wireless Section Membership Sub-Committee should scrutinize all new applications for membership of the Wireless Section and decide who shall be admitted to it. The Sub-Committee should be authorized to call for full particulars as to the nature of the study undertaken by an applicant or for particulars of his work in design, manufacture or operation, in order to satisfy themselves that the applicant is properly qualified in wireless engineering.

(3) The fact should be emphasized and more widely published that the meetings of the Wireless Section are open to all members of the Institution.

(4) The Wireless Section Committee should get into direct touch with the Local Centre Committees, for the purpose of :—

(*a*) Ascertaining the possibility of starting Local Wireless Sections.
(*b*) Stimulating efforts to produce local wireless papers.
(*c*) Suggesting the reading of suitable papers or the giving of lectures at Local Centres.

(5) Each Local Wireless Section, when properly constituted, should be entitled to elect or nominate one member to the Wireless Section Committee. For this purpose, a Local Wireless Section should consist of at least 15 members, who must already be members of the main Wireless Section.

(6) The papers and the discussions of the Wireless Section, and other wireless papers, in addition to appearing in the *Journal* of the Institution, should be issued separately in the form of "Proceedings of the Wireless Section."

(7) As soon as the necessary alterations to the Bye-laws can be made, the Chairman of the Wireless Section Committee should be an *ex-officio* member of Council, in the same way as are the Chairmen of Local Centres (in the meantime he will be invited to attend all meetings of the Council).

(11) Informal Meetings.

Eleven meetings have been held during the session, the average attendance being 65, as against 59 last year.

A new feature was introduced during the Session by holding a meeting at the Rockefeller Building, University College, Gower-street, where Mr. W. C. Clinton, B.Sc., opened a discussion on the electrical installation of the building.

The primary object of the meetings is to encourage the younger members to participate in discussions on technical subjects, and the Council would like to see fuller advantage taken of these fortnightly gatherings.

The précis of the meetings which appear in the technical Press are carefully prepared, and any statements by speakers likely to be questioned or to cause controversy are omitted.

(12) Students' Sections.

There are at present 3 586 Students on the Register of the Institution, and a very full programme of meetings, visits to works, and social functions has been carried out at the eight Students' Sections now in existence, viz. at London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle and Sheffield.

Addresses to the London Students' Section were given by the President and Lt.-Col. K. Edgcumbe, R.E. (T.A.), Vice-President. The President also addressed the South Midland Students' Section.

The London Students' Section created an interesting precedent last summer by holding a Summer Meeting in London, and it was attended by, in addition to London Students, some 20 Students from the provinces and Scotland.

The Meeting, which began on Saturday evening, the 25th July, with a Smoking Concert, was continued as follows :—

Sunday.	A trip up the Thames to Chertsey and back, by steam launch.
Monday.	Visit to the Woolwich works of Messrs. Siemens Bros. and Co., Ltd.
Tuesday.	A motor tour through Kent and Surrey.
Wednesday.	Visit to Wembley Exhibition.
Thursday.	Visit to the Marconi stations at Ongar and Brentwood.
Friday.	Visit to the Research Laboratories of the General Electric Co., Ltd., Wembley.
Saturday.	Visit to the Beckton works of the Gas Light and Coke Co., Ltd.

The proceedings were brought to a close on the Saturday evening (the 1st August) by a farewell Dinner at the Holborn Restaurant.

The Council desire to express the thanks of the Institution for the hospitable welcome extended on the occasion of the visits to works, etc.

The meeting was very successful and thanks are due to the then Hon. Secretary (Mr. J. H. Reyner) and the Committee of the London Students' Section for the excellent arrangements made by them.

(13) Faraday Lecture.

The Faraday Lecture this session was given by Mr. A. P. Trotter, who took for his subject "Illumination

and Light," and it was delivered at Cardiff, Dublin, Liverpool and Manchester. The attendances were very satisfactory, and the principal object of the Lecture, namely, to direct the attention of the general public to electrical engineering, was achieved to a marked degree by the presence of many hundreds of non-members.

(14) REVIEWS OF PROGRESS.

The Council decided this session to publish in the *Journal* periodical reviews of progress in electrical engineering, and for this purpose the subject has been divided into the following 13 sections :—

*Electrical Plant and Machinery (including Marine Work).
*Power Stations and their Equipment.
Transmission and Distribution.
Industrial, Agricultural and Domestic Applications (including Illumination and Tariffs).
Electricity in Mining.
Traction.
Electrical Measuring Instruments and Sensitive Controlling Apparatus.
*Telegraphy and Telephony.
Radio-telegraphy and Radio-telephony.
Electro-chemistry and Electro-metallurgy.
*Electro-physics.
*Research.
*Standardization.

Whilst it is hoped eventually to publish each year reviews of all the sections, a beginning has been made this year with the sections marked with an asterisk. A further selection will appear in 1927, and subsequent action will be based on the experience gained during the first two years.

These reviews have been prepared for the purpose of briefly recording recent advances, and they are intended, not so much for the information of experts in the particular subject under review, as for the information of those members of the Institution who wish to follow the trend of progress in branches of electrical engineering other than their own.

The Council will be glad if members will forward to the Secretary of the Institution any criticisms which they may wish to make on the present reviews, and also on the ground to be covered by those to be published in the future, more especially in regard to points of interest which come under their notice and on which they consider comment might usefully be made.

(15) SCHOLARSHIPS.

The following Scholarships have been awarded by the Council :—

A David Hughes Scholarship.

(Value £50 ; tenable for one year.)

G. N. Peel, B.Sc. (Armstrong College, Newcastle-upon-Tyne).

Salomons Scholarships.

(Value £50 each ; tenable for one year.)

R. O. Carter [City and Guilds (Engineering) College, London].

H. S. Leman (East London College, London).

War Thanksgiving Education and Research Fund (No. 1).

A grant of £100 for educational purposes has been made by the Council, under the provisions of the Trust Deed, to F. W. Rudge (Royal Technical College, Glasgow).

(16) ANNUAL CONVERSAZIONE.

The Annual Conversazione was held at the Natural History Museum, South Kensington, London, on the 2nd July, 1925, when about 1 400 members and guests attended.

The Conversazione in 1926 will be held at the Science Museum, South Kensington, instead of the Natural History Museum.

(17) ANNUAL DINNER.

The Annual Dinner was held at the Hotel Cecil, London, on the 11th February, 1926, and was particularly well attended, the members and guests present numbering 575.

An account will be found in the *Journal*, 1926, vol. 64, p. 436.

(18) SUMMER MEETING.

A Summer Meeting attended by some 350 members and ladies was held at Birmingham, from the 9th to the 12th June, 1925, by invitation of the Committee of the South Midland Centre, who had arranged an interesting programme of functions, excursions and visits to works.

The works visited during the Meeting were as follows :—

The Austin Motor Co.'s works, Longbridge.
The Prince's power station of the City of Birmingham at Nechells, and the mercury-arc rectifier substation at Longbridge.
The British Thomson-Houston Co.'s works, Rugby.
The General Electric Co.'s works, Witton.
The Shropshire, Worcestershire and Staffordshire Electric Power Co.'s new power station, under construction at Stourport.

Other places visited were Droitwich, Evesham, Stratford-on-Avon and Warwick.

The visitors enjoyed the hospitality of :—

The Lord Mayor and Lady Mayoress of Birmingham.
The City of Birmingham Electric Supply Department.
The Council and Senate of the University of Birmingham.
The British Thomson-Houston Co., Ltd.
The General Electric Co., Ltd.
The Leamington and Warwick Electrical Co., Ltd.
The Leicestershire and Warwickshire Electric Power Co.
The Midland Electric Light and Power Co., Ltd.
The Shropshire, Worcestershire and Staffordshire Electric Power Co.

The Council have expressed the cordial thanks of the Institution to all those named. They also wish to place on record their high appreciation of the work of the Committee of the South Midland Centre in making the arrangements for the Meeting, and particularly of that of the Chairman of the Centre (Mr. W. Lawson) and the Hon. Secretary (Mr. H. Hooper).

(19) Paris International Conference on Large E.H.T. Supply Systems.

The third session of the above Conference took place in Paris from the 16th to the 25th June, 1925. The number of countries represented was 27, Great Britain being represented by 7 delegates appointed by the Institution, and 21 ordinary members. The Institution's delegates were Mr. W. B. Woodhouse (chief delegate), Mr. A. R. Everest, Mr. P. V. Hunter, C.B.E., Mr. R. B. Matthews, Mr. A. Page, Mr. G. V. Twiss, and Mr. E. B. Wedmore.

The number of papers presented was 98.

(20) New York Meeting of the International Electrotechnical Commission.

A meeting of the International Electrotechnical Commission will be held at New York in April, 1926. Sixteen countries will be represented and there will be some 24 British delegates under the leadership of Sir R. T. Glazebrook, D.Sc., F.R.S. The delegates appointed by the Council to represent the Institution are Mr. C. P. Sparks, C.B.E., Lt.-Col. K. Edgcumbe, R.E. (T.A.), Mr. S. W. Melsom, and the Secretary.

(21) Wireless Telegraphy and Signalling Bill.

The above Bill, in regard to which the Council made certain representations to the Postmaster-General, as mentioned in the last Annual Report, was not proceeded with by the Government.

(22) Engineering Institute of Canada.

Mr. Frank Gill, Past-President, who was on a visit to Canada in June, 1925, was on that occasion the bearer of greetings and of a message of goodwill from the Institution to the Canadian Institute. The following message has since been received in response :—

"The Council of the Engineering Institute of Canada was gratified to receive the kind messages of the Council of the Institution of Electrical Engineers, and was particularly pleased to have the opportunity of welcoming the Institution's Past-President, Mr. Frank Gill. It is the Council's hope that, in the future, more frequent opportunities will occur for the interchange of friendly messages with the Institution."

(23) The Society of Radiographers.

The Council, who took an important part in founding the Society of Radiographers in the year 1920, and who, under that Society's constitution, had until last year nominated six out of the 18 members of the Society's Council, have withdrawn their nominees and terminated the Institution's connection with the Society.

This action was taken because the majority of the Council of the Society of Radiographers resolved upon certain alterations to the Society's Articles, which, in the opinion of the Council of the Institution, were not in the public interest.

(24) The Institution of Municipal and County Engineers.

The Council received in November, 1925, a letter from the Privy Council enclosing a Petition for, and a Draft of, a Charter of Incorporation applied for by the above Institution, together with a copy of a petition of the Institution of Civil Engineers, and asking for any observations the Council might have to offer thereon.

After due consideration the Council intimated to the Privy Council that, in their opinion, so far as Engineering Bodies are concerned, a Charter should be granted only to those which grant diplomas based solely on technical qualifications and not on the holding of a particular type of appointment, and on that ground they are not in favour of a Charter being granted to the Institution of Municipal and County Engineers.

(25) Model General Conditions for Contracts.

The September, 1921, edition of the Model Conditions "A" (Home—With Erection) has been amended to make it clear that the Regulations and Bye-Laws with which the Contractor has to conform are those which the Local or other Authorities are authorized by Statute to make. In Clause 37 of the new edition (revised January, 1926) the words "which they are authorized by Statute to make and" have been inserted after the word "Authorities." The new edition in all other respects conforms with the old edition.

The following sets of Conditions were also issued during the Session :—

B1. Conditions for Export Contracts (Delivery F.O.B.).

B2. Conditions for Export Contracts (including complete erection or supervision of erection).

(26) Technical Committees.

The former five "Sectional Committees," viz.

Electro-chemistry and Electro-metallurgy,
Electricity in Mines,
Lighting and Power,
Telegraphs and Telephones,
Traction,

have been reorganized as nine Committees, to be known in future as "Technical Committees," as follows :—

Electrical Plant and Machinery (including Marine Work).
Power Stations and their Equipment.
Transmission and Distribution.
Industrial, Agricultural and Domestic Applications (including Illumination and Tariffs).
Electrical Measuring Instruments and Sensitive Controlling Apparatus.
Traction.
Electricity in Mines.
Electro-chemistry and Electro-metallurgy.
Telegraphs and Telephones.

The functions of the Committees will be to obtain suitable papers on subjects within their respective fields and to assist the Papers Committee in connection with the Reviews of Progress referred to in par. (14) of this Report.

(27) Gas and Electricity Undertakings.

With the concurrence of the Council of the Institution and of the National Gas Council, a Joint Committee has been set up with the following reference :—

"To consider whether in the national interest an Inquiry might advantageously be held into the

possibility of closer co-operation between Gas and Electricity Undertakings in promoting capital and fuel economy in the supply to the public of energy derived from coal"

with the understanding that no Reports or Discussions of the Committee are to be published without the consent of both Councils.

The Committee is constituted as follows :—

Mr. R. A. Chattock Mr. J. S. Highfield Mr. G. W. Partridge Mr. C. P. Sparks, C.B.E. Mr. W. B. Woodhouse	Nominated by the Council I.E.E.
Mr. D. Milne Watson, D.L. Mr. W. Cash, F.C.A. Sir A. Duckham, K.C.B. Mr. A. W. Smith Mr. C. Wood, O.B.E., F.C.S.	Nominated by the National Gas Council.

(28) Library.

During the year **163** books and pamphlets have been presented to the Reference Library by members and others, and **80** volumes have been purchased. The total number of readers for the year was 3 537, of whom **114** were non-members, as against **2 419** and **108** respectively in 1924–1925.

The Council have pleasure in recording the continued circulation of books from the Lending Library, to which **71** new volumes have been added. During the year, **1 938** books were issued to **857** borrowers, the corresponding numbers for the previous year being **2 184** and **872** respectively.

A new edition of the Lending Library Catalogue with a subject index is now available, and copies will be forwarded to members on application to the Secretary.

(29) Gifts to the Institution.

The Council have pleasure in recording the following gifts to the Institution, and express their cordial thanks to the donors :—

Donor.	*Gift.*
The Eastern Telegraph Co., Ltd.	A Thomson (Lord Kelvin) marine-pattern galvanometer.
Mr. Napier Prentice . .	Lane-Fox lamp.

(30) Electrical Appointments Board.

The number of applicants for posts who were registered on the 31st March, 1926, was 87, against a total of 78 last year.

A classified register of members seeking positions, containing particulars of their training and experience, is available for inspection at the Institution offices, and the Secretary of the Board will gladly put employers in touch with highly qualified electrical engineers.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the register.

(31) The Journal of the Institution.

The net cost of printing and posting the *Journal* in 1925, after allowing for sales and the revenue received from advertisements, was **£4 166**, as compared with **£3 078** in **1924**. This increase was due to the greater size of the volume (**1 180** pages as compared with **1 006** in the previous volume), the larger number of copies printed (**12 500** as against **12 000**) and an appreciable increase in the number of illustrations. The revenue from sales and advertisements was practically the same in the two years.

(32) "Science Abstracts."

The Physics volume of *Science Abstracts* for **1925** contained **195** pages less than for **1924**, and the Electrical Engineering volume contained **39** pages more than in the previous year. The Accounts show that the net cost of the publication to the Institution in **1925** was **£281**, which the Council consider satisfactory.

The Council deeply regret to have to record the death of Mr. W. R. Cooper, M.A., B.Sc., who had so ably edited the publication since October, 1922.

(33) Committee on Electricity in Agriculture.

The Report of the above Committee has been presented to the Council and was published in the *Journal* (1925, vol. 63, p. 838).

On the recommendation of the Committee, the Council have instructed them (1) to prepare a special recommendation to the Government in connection with the provision of financial assistance for rural electrification and (2) to co-operate with agricultural bodies in tests and experimental work.

The Council have also addressed a letter to the Electricity Commissioners urging that, in any schemes of railway electrification, regard should be had to the requirements of rural areas.

(34) National Certificates and Diplomas in Electrical Engineering.

For the final examinations of the year **1925** the Joint Standing Committee representing the Board of Education and the Institution examined at various schools and colleges students from **46** approved courses for the award of Ordinary Certificates in Electrical Engineering, **17** courses for Higher Certificates, **3** courses for Ordinary Diplomas and **1** course for Higher Diplomas.

The final examinations were held during the summer of **1925** and the number of Certificates and Diplomas awarded was as follows :—

229 Ordinary Certificates.
79 Higher Certificates.
8 Ordinary Diplomas.
2 Higher Diplomas.

(35) Regulations for the Electrical Equipment of Ships.

The Council have authorized the publication of a revised edition, the second, of the Regulations.

(36) Regulations for the Electrical Equipment of Buildings.

As a result of comments and suggestions received in connection with the revised edition of the Wiring Regulations, the Wiring Rules Committee recommended the Council last summer to publish a small number of amendments which were considered to be of sufficient importance to justify their immediate publication. Further alterations have been, and some still are, under consideration by the Committee and, if not published separately, will be incorporated in the next revision of the Regulations. The Committee are also conferring with the B.E.A.M.A. and the B.E.S.A. in connection with certain of the Regulations.

(37) Electricity Regulations.

The Council have approved for submission to the Electricity Commissioners a Report from the Electricity (Supply) Regulations Committee containing recommendations on the Electricity Commissioners' Regulations (A) for securing the safety of the Public, and (B) for ensuring a proper and sufficient supply of Electrical Energy.

(38) Proving House.

During the session the Council received and approved the following Report of the Proving House Committee:

"Having in view that there appears to be very little interest in the establishment of a Testing Authority and Proving House, as has been evidenced by the poor attendance at the meetings held, and considering that the purpose of the Authority, viz. to decide whether apparatus complies with some recognized standard or specification, does not meet the whole of the requirements of those desiring the establishment of the Authority and Proving House, and, further, as no adequate financial support is forthcoming, the Committee recommend to the Council that the proposal be dropped.

"The Committee further desire the Council to note that it has been reported that most of the services of such an Authority, so far as testing is concerned, can be obtained on payment from the National Physical Laboratory, the Manchester Corporation, and other public and also several private laboratories."

(39) Status of Engineer Officers, R.N.

In December, 1925, the Council received an invitation from the Institution of Mechanical Engineers to nominate representatives to join a delegation which the First Lord of the Admiralty had consented to receive on the status of Engineer Officers of the Royal Navy, which, it was considered, was detrimentally affected by the new conditions introduced by Fleet Order No. 3241, of the 21st November, 1925.

Representatives were duly appointed and these met in conference delegates of the Institutions of Civil and of Mechanical Engineers and of the Institution of Naval Architects, when a memorandum was prepared for submission to the First Lord.

The deputation was received at the Admiralty on the 14th January, 1926, and laid before the First Lord the objections of the four Institutions to the changes effected by the Fleet Order in question, the principal change being the deprival of Engineer Officers of the executive rank which they had held in common with deck officers since 1915.

A reply has since been received stating that, in the view of the Admiralty, there are no real grounds for grievance and that experience will convince the Engineer Officers of the Navy that there is nothing in the Order derogatory to their position.

The reply is considered by the members of the joint Conference as unsatisfactory and steps are being taken to carry the matter a stage further.

(40) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1925, the Capital Account of the Fund stood at £10 004 11s. 3d., and the accumulated income at £2 380 9s. 6d. The donations and subscriptions to the Fund in 1925 amounted to £1 241 3s. 7d.

In the course of 1925, 78 grants were made to 30 persons, amounting to a total of £1 199 5s. 1d. The following table summarizes the operations of the Fund during the last 10 years:—

Year	Subscriptions and donations received	Total grants made during year	No. of cases assisted
	£	£	
1916	239 100 (Legacy)	195	7
1917	194	198	11
1918	259	230	10
1919	537	291	12
1920	821	341	11
1921	616 809 (Hughman collection)	525	14
1922	632 1 768 (Hughman collection)	776	16
1923	637	1 034	21
1924	1 152	1 323	26
1925	1 241	1 199	30

(41) Annual Accounts.

Excess of Income over Expenditure.—After making provision for contingencies, there is a margin to the good on the Revenue Account for 1925 of £1 196 8s. 11d. This amount, which has been carried to the credit of the General Fund, compares with £2 925 0s. 8d. in 1924.

Mortgage.—

	£	s.	d.
In the Accounts for 1924 this stood at	13 721	2	0
Amount of repayments during the year	1 127	5	10
The amount now stands at	£12 593	16	2

Assets.—Taking the Tothill-street property and the investments at cost, and the Institution Building and

lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d.
the Assets amount to	145 336	5	0
against Liabilities	8 007	12	10
leaving a surplus of	137 328	12	2
which, in comparison with that of the year 1924, viz.	133 016	0	11
shows an improvement of	£4 312	11	3

The surplus referred to above of £137 328 12s. 2d. is made up as follows :—

Assets.	£	s.	d.	£	s.	d.
Institution Building and Tothill-street Property	92 289	3	11			
Less Mortgage	12 593	16	2			
				79 695	7	9
Investments, Cash, etc.				57 689	8	11
Stock of Paper, Libraries and Furniture ..				7 951	8	4
				£145 336	5	0
Less *Liabilities.*						
Trust Fund Income Accounts	468	11	1			
Sundry Creditors ..	5 344	18	4			
Repairs Suspense Account	1 795	5	8			
Subscriptions received in advance	398	17	9			
				8 007	12	10
				£137 328	12	2

(42) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED.

Appendix C shows in diagram form the organization of the Institution and the bodies on which it is represented.

APPENDIX A.

MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since 1st April, 1925, are shown in the following table :—

	Hon. Mem.	Mem.	Assoc. Mem.	Grad.	Studt.	Assoc.	Total.	TOTAL.
Totals at 1 April, 1925	10	1 881	4 698	1 332	3 481	341		11 743
Additions during the year :—								
Elected ..		6	69	183	679	2	939	
Reinstated ..		1	16	1	29	1	48	
Transferred to	1	66	118	232	..	..	417	
Total	1	73	203	416	708	3	1 404	

		Mem.	Assoc. Mem.	Grad.	Studt.	Assoc.	Total.	TOTAL.
Deductions during the year :—								
Deceased ..		29	23	3	10	2	67	
Resigned ..		13	25	19	77	6	140	
Lapsed ..		15	72	56	228	10	381	
Transferred from ..		1	65	60	288	3	417	
Total	—	58	185	138	603	21	1 005	
Net Increase								399
Totals at 1 April, 1926	11	1 896	4 716	1 610	3 586	323		12 142

APPENDIX B.

MEETINGS.

The following is a list of the meetings held during the past twelve months :—

Ordinary Meetings ..	15
Wireless Section Meetings	8
Informal Meetings ..	12
Council Meetings ..	18
Local Centres :—	
Irish	6
Mersey and North Wales (Liverpool) ..	7
North-Eastern ..	11
North Midland ..	11
North-Western ..	11
Scottish	7
South Midland ..	10
Western	10
Local Sub-Centres :—	
Dundee	7
East Midland ..	9
Sheffield	7
Tees-side	7
Students' Sections :—	
London	8
South Midland ..	9
North Midland ..	11
Liverpool	8
North-Western ..	9
North-Eastern ..	12
Scottish	9
Sheffield	5
Committees :—	
Benevolent Fund ..	6
Earthing to Water Mains	3
Electricity in Agriculture	1
Electricity (Supply) Bill	2
Electricity (Supply) Regulations ..	16
Examinations (and Sub-Committee) ..	7
Committees (*cont.*) :—	
Finance (and Sub-Committee) ..	8
General Purposes (and Sub-Committee) ..	14
Informal Meetings ..	5
Lighting and Power ..	1
Membership	11
Model General Conditions (and Sub-Committee) ..	3
Model General Conditions (Export) ..	1
Papers	10
Paul Scholarship ..	3
Proving House ..	2
"Science Abstracts"	5
Ship Electrical Equipment (and Sub-Committee) ..	1
Supply Pressures ..	1
Technical Committees : ("Instruments," "Mines," "Power Stations," "Applications," "Telegraphs and Telephones," "Traction," "Transmission")	9
Wireless Section (and Sub-Committee) ..	11
Wireless Telegraphy Bill	1
Wiring Rules (and Sub-Committees) ..	11
Other Committees ..	15
Total	374

APPENDIX C.

THE INSTITUTION OF ELECTRICAL ENGINEERS.

- Ordinary Meetings
- Wireless Section Meetings
- Informal Meetings
- Meetings of London Students' Section

COUNCIL.

Local Centres.
- Argentina
- China
- Irish
- Mersey and North Wales (Liverp'l)
  - †Mersey and North Wales (Liverp'l) S.S.
- North-Eastern
  - *Tees-side S.C.
  - †North-Eastern S.S.
- North Midland
  - †North Midland S.S.
  - *Sheffield S.C.
  - †Sheffield S.S.
- North-Western
  - †North-Western S.S.
- Scottish
  - *Dundee S.C.
  - †Scottish S.S.
- South Midland
  - *East Midland S.C.
  - †South Midland S.S.
- Western

* S.C.=Sub-Centre.

† S.S.=Students Section.

COMMITTEES.
(Standing.)

Benevolent Fund
Electrical Appointments Board
Examinations
Finance
General Purposes
Informal Meetings
Library
Local Centres
Membership
Papers
Paul Scholarship
"Science Abstracts"
Ship Electrical Equipment
Wireless Section
Wiring Rules

Technical Committees.
- Electrical Measuring Instruments and Sensitive Controlling Apparatus
- Electrical Plant and Machinery, including Marine Work
- Electricity in Mines
- Electro-chemistry and Electro-metallurgy
- Industrial Agricultural and Domestic Applications, including Illumination and Tariffs
- Power Stations and their Equipment
- Telegraphs and Telephones
- Traction
- Transmission and Distribution

COMMITTEES.
(Special.)

Earthing to Water Mains
Electricity in Agriculture
Electricity (Supply) Bill
Electricity (Supply) Regulations
Examinations Sub-Committee
Model General Conditions
Proving House
Supply Pressures
Wireless Telegraphy Bill

BODIES ON WHICH THE INSTITUTION IS REPRESENTED.

Alloys of Iron Research (Royal Society)
Association of Teachers in Technical Institutions (Special Committee)
Birmingham Chamber of Commerce
Bradford Public Libraries Committee
Bristol University
British Cast Iron Research Association
British Electrical and Allied Industries Research Association
British Electrical Development Association
British Engineering Standards Association
British National Committee of the International Electrotechnical Commission
British National Illumination Committee of the International Illumination Commission
Conference on Smoke Abatement, 1926
Corrosion Research Committee of Institute of Metals
Electric Vehicle Committee of Great Britain
Engineering Joint Council
Fifth International Road Congress, 1926
Imperial College of Science and Technology, Governing Body
Imperial Mineral Resources Bureau Conference
Institution of Civil Engineers, Engine and Boiler Testing Committee
Institution of Heating and Ventilating Engineers, Committee on Utilization of Exhaust Steam and Waste Heat
International Electrotechnical Commission, U.S.A., 1926
International Scientific Unions
Leeds Civic Society
Leeds Municipal Technical Library Committee
Loughborough Technical College Advisory Committee
Metalliferous Mining (Cornwall) School, Governing Body
Middlesbrough Technical College, Governing Body
National Committee for Physics (Royal Society)
National Committee on Radio Telegraphy (Royal Society)
National Physical Laboratory, General Board
National Register of Electrical Installation Contractors
Professional Classes Aid Council
Royal Engineer Board
Royal Sanitary Institute Jubilee Congress, 1926

(Continued at foot of col. 1.)

(Continued from foot of col. 3.)

Standing Joint Committee on Gas and Electricity
Standing Joint Committee for National Certificates and Diplomas in Electrical Engineering
Union of Lancashire and Cheshire Institutes, Panel for Engineering
Women's Electrical Association
Women's Engineering Society
World Power Conference; British National Committee

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1925.

Dr. EXPENDITURE.

Year ended 31 Dec., 1924. £ s. d.		£ s. d.	£ s. d.
	To MANAGEMENT :—		
	Salaries and Wages (including Staff Provident Scheme)	11,419 6 6	
	National Insurance	56 7 4	
	Audit Fee	42 0 0	
	Printing	773 3 9	
	Stationery and Office Requisites	469 2 5	
	Addressing	33 18 4	
	Postage of Correspondence and Notices	577 14 7	
	Telephone	62 0 0	
	Travelling Expenses	175 7 8	
	Bank Charges	16 14 8	
12,643 19 9			13,625 15 3
	„ INSTITUTION BUILDING :—		
	Ground Rent	2,201 0 0	
	Rates	2,935 4 6	
	Heating	315 6 9	
	Lighting and Power	303 8 6	
	Insurance	155 8 4	
	Reserve for Repairs	1,500 0 0	
	Household Requisites and Cleaning	261 4 7	
	Estate Agents' Fees	52 10 0	
	Re-wiring	3,786 13 7	
		11,510 16 3	
	Less Rents from Tenants	5,597 10 0	
3,858 4 0			5,913 6 3
594 15 1	„ INTEREST ON MORTGAGE		547 6 11
64 15 0	„ FURNITURE AND FITTINGS (Repairs and Renewals)		134 12 6
	„ JOURNAL :—		
	Printing	6,085 10 5	
	Postage	1,774 4 7	
	Wrappers and Envelopes	220 17 11	
		8,080 12 11	
	Less Sales and Advertisements	3,914 19 0	
3,078 7 5			4,165 13 11
126 11 0	„ LENDING LIBRARY (Books, Printing, Postage, etc.)		100 7 3
	„ SCIENCE ABSTRACTS :—		
	Salaries, Abstracting, Printing, Postage, etc.	4,318 2 5	
	Less Subscriptions, Sales, and Advertisements	4,037 10 7	
68 11 4			280 11 10
	Carried Forward		£24,767 13 11

INCOME. Cr.

Year ended 31 Dec., 1924. £ s. d.		£ s. d.	£ s. d.
30,223 4 7	By SUBSCRIPTIONS		30,694 15 2
745 10 0	„ ENTRANCE FEES AND VELLUM DIPLOMA FEES		781 15 0
—	„ LIFE COMPOSITIONS		163 18 1
2,115 2 10	„ DIVIDENDS AND INTEREST		2,487 19 6
212 4 0	„ MODEL GENERAL CONDITIONS		208 11 5
92 4 11	„ WIRING REGULATIONS		147 10 2
10 5 5	„ SHIP WIRING REGULATIONS		0 4 6
	„ TOTHILL STREET PROPERTY :—		
	Rents from Tenants	1,290 0 0	
	Less Ground Rent, Repairs, Alterations, Rates, Taxes, etc.	419 3 2	
509 0 5			870 16 10
	„ EXAMINATIONS :—		
	A.M.I.E.E. Examination (Fees, *less* Expenses)	29 7 7	
	National Certificates and Diplomas (Fees *less* Expenses)	235 11 6	
254 5 3			264 19 1
	Carried Forward		£35,620 9 9

REVENUE ACCOUNT—*continued.*

Dr. EXPENDITURE—*continued.*

1924		£ s. d.	£ s. d.
	Brought Forward		24,767 13 11
	To INSTITUTION MEETINGS :—		
	Advance Proofs	183 13 5	
	Reporting	113 8 0	
	Grant to London Students' Section ...	29 5 8	
	Honorarium to Kelvin Lecturer	25 0 0	
	Refreshments, Assistance, etc.	222 18 4	
	Travelling Expenses of Authors of Papers	72 3 8	
	Faraday Lectures	191 13 9	
684 6 5			838 2 10
	" LOCAL CENTRES :—		
	Money Grants (including Travelling Expenses of Authors of Papers) ...	2,247 2 0	
	Travelling Expenses	601 15 6	
2,654 4 2			2,848 17 6
204 2 3	" PREMIUMS FOR PAPERS		213 10 9
	" SPECIAL GRANTS :—		
	British Engineering Standards Association	500 0 0	
	Electrical Research Association... ...	500 0 0	
	National Illumination Committee ...	32 0 0	
	International Conference on Extra-High-Tension Systems	141 2 6	
910 0 0			1,173 2 6
137 4 0	" ANNUAL DINNER		124 10 3
525 18 10	" CONVERSAZIONE...		488 8 10
43 18 0	" LEGAL EXPENSES		7 7 0
68 13 10	" MISCELLANEOUS EXPENSES		145 13 4
25,663 11 1			30,607 6 11
	" AMOUNTS TRANSFERRED TO :—		
277 12 2	SINKING FUND (Premiums for Redemption of Cost of Building and Lease) ...	277 12 2	
3,500 0 0	RESERVE FUND (Contingencies and Mortgage Redemption)	2,000 0 0	
	GENERAL FUND :—		
1,080 17 4	Obligatory Repayment to Economic Life Assurance Society	1,127 5 10	
—	Life Compositions received in 1925 (*per contra*)	163 18 1	
	Expenditure on—		
323 15 11	Books and Binding for Library ...	183 17 10	
391 0 3	Furniture, Fittings and Apparatus	64 0 0	
2,925 0 8	**Balance carried to General Fund** ...	1,196 8 11	
			5,013 2 10
34,161 17 5			£35,620 9 9

INCOME—*continued.* **Cr.**

1924		£ s. d.
	Brought Forward	35,620 9 9
34,161 17 5		£35,620 9 9

BALANCE SHEET, 31ST DECEMBER, 1925.

Dr. — LIABILITIES.

	£ s. d.	£ s. d.
To ECONOMIC LIFE ASSURANCE SOCIETY :—		
On Mortgage of Institution Building (1900) ...	26,000 0 0	
Since repaid	13,406 3 10	
		12,593 16 2
„ KELVIN LECTURE FUND :—		
As per last Balance Sheet		648 13 0
„ UNINVESTED BALANCES OF TRUST FUNDS		468 11 1
„ SUNDRY CREDITORS		5,344 18 4
„ SUBSCRIPTIONS RECEIVED IN ADVANCE		398 17 9
„ REPAIRS SUSPENSE ACCOUNT :—		
Balance at 1st January, 1925	1,208 12 1	
Amount set aside in 1925	1,500 0 0	
	2,708 12 1	
Less Expenditure on Repairs in 1925... ...	913 6 5	
		1,795 5 8
„ RESERVE FUND (Contingencies and Mortgage Redemption) :—		
Balance at 1st January, 1925	17,500 0 0	
Amount transferred to Reserve Fund in 1925 ...	2,000 0 0	
		19,500 0 0
Carried Forward		40,750 2 0

ASSETS. — **Cr.**

	£ s. d.	£ s. d.
By INSTITUTION BUILDING AND LEASE :—		
Cost	73,028 6 10	
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	5,161 2 8	
		67,867 4 2
„ SINKING FUND (Surrender Values of Policies for Redemption of Cost of Building and Lease)		5,161 2 8
„ TOTHILL STREET BUILDINGS AND SITE (at cost)		19,260 17 1
„ KELVIN LECTURE FUND INVESTMENT (at cost) :—		
£694 16s. 9d. 5 % War Stock (1929–47)		648 13 0
„ LIBRARY (exclusive of the Ronalds Library and Faraday Papers, which are held in trust) :—		
As per last Balance Sheet	1,245 5 1	
Additions in 1925	183 17 10	
	1,429 2 11	
Less Depreciation (10 %)	142 18 4	
		1,286 4 7
„ THOMPSON MEMORIAL LIBRARY (Contribution towards purchase)		1,000 0 0
„ FURNITURE, FITTINGS, AND APPARATUS :—		
As per last Balance Sheet	5,537 1 3	
Expenditure in 1925	64 0 0	
	5,601 1 3	
Less Depreciation (5 %)	280 1 1	
		5,321 0 2
„ SUNDRY DEBTORS		3,990 10 3
„ INSURANCE PREMIUMS AND SUNDRY PAYMENTS IN ADVANCE ...		595 17 1
„ STOCK OF PAPER, ETC., FOR PUBLICATIONS		344 3 7
Carried Forward		105,475 12 7

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued.*

		£ s. d.	£ s. d.
Brought Forward			40,750 2 0
To **General Fund** :—			
Balance at 1st January, 1925		114,867 7 11	
Obligatory Repayment to Economic Life Assurance Society		1,127 5 10	
Life Compositions received in 1925		163 18 1	
Expenditure in 1925 on—			
Books and Binding for Library		183 17 10	
Furniture, Fittings and Apparatus		64 0 0	
Balance from Revenue Account for 1925 ...		1,196 8 11	
		117,602 18 7	
Less Depreciation :—			
Library (*per contra*)	£142 18 4		
Furniture, Fittings, and Apparatus (*per contra*)	280 1 1		
		422 19 5	
			117,179 19 2
			£157,930 1 2

P. D. TUCKETT,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

ASSETS—*continued.* **Cr.**

	£ s. d.	£ s. d.
Brought Forward		105,475 12 7
By **General and Reserve Funds Investments** (at cost) :—		
£2,600 Natal Zululand Railways 3 % Debenture Stock	2,270 12 0	
£1,500 London, Midland and Scottish Railway 4 % Preference Stock	1,513 10 4	
£2,000 Assam Bengal Railways 3 % Stock (1931 or after)	1,548 0 6	
£750 Western Australia 4 % Stock (1942–62) ...	730 8 3	
£750 Union of South Africa 4 % Stock (1943–63) ...	742 12 0	
£750 Madras and Southern Mahratta Railway 4 % Debenture Stock (1938)	738 15 6	
£35 East Indian Railway "B" Annuity (1953) ...	791 5 4	
£1,500 South Australia 4% Stock (1940–60)... ...	1,494 10 6	
£5,250 5 % War Stock (1929–47)	4,987 10 0	
£2,000 5 % National War Bonds (1929)	2,000 0 0	
£3,000 5 % National War Bonds (1928)	3,206 11 0	
£19,375 4 % Funding Loan (1960–90)	15,500 0 0	
£8,700 3½ % Conversion Stock (1961 or after) ...	6,651 3 3	
£5,000 5 % Treasury Bonds (1927)	5,084 15 6	
£1,000 London, Midland and Scottish Railway 5% Preference Stock (1955)	1,020 4 6	
		48,279 18 8
„ **Cash in Hands of Local Centres on 30 Sept.**, 1925		838 10 2
„ **Cash** :—		
At Bankers'	3,163 18 10	
In hands of Secretary	172 0 11	
		3,335 19 9
		£157,930 1 2

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1925, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

21st April, 1926.

ALLEN, ATTFIELD & CO., ***Auditors***,
Chartered Accountants,
24, **Martin Lane, Cannon Street, E.C. 4.**

SALOMONS SCHOLARSHIP TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,155 14 10	By Investments (at cost) :—	
		£1,528 5s. 1d. New South Wales 5% Stock (1935–55)	1,585 1 4
		£500 Cape of Good Hope 3½% Stock (1929–49)	570 13 6
	£2,155 14 10		£2,155 14 10

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1925	62 10 0	By Balance (as per last Account)	33 7 4
„ Balance carried to Balance Sheet *	62 6 10	„ Dividends received in 1925	91 9 6
	£124 16 10		£124 16 10

DAVID HUGHES SCHOLARSHIP TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,000 0 0	By Investment (at cost) :—	
		£2,045 Metropolitan Water Board (Staines Reservoirs) 3% Guaranteed Debenture Stock (1922 or after)	1,998 15 0
		„ Balance carried to Balance Sheet *	1 5 0
	£2,000 0 0		£2,000 0 0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1925	50 0 0	By Balance (as per last Account)	31 19 4
„ Balance carried to Balance Sheet *	43 0 8	„ Dividends received in 1925	61 0 10
		„ Interest do. do.	0 0 6
	£93 0 8		£93 0 8

PAUL SCHOLARSHIP FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	500 0 0	By Investment (at cost) :—	
		£625 4% Funding Loan (1960–90)	500 0 0
	£500 0 0		£500 0 0

PAUL SCHOLARSHIP FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Balance carried to Balance Sheet *	75 0 0	By Balance (as per last Account)	50 0 0
		„ Dividends received in 1925	25 0 0
	£75 0 0		£75 0 0

* Included in the total of £468 11s. 1d. shown on the Liabilities side of the Balance Sheet.

WILDE BENEVOLENT TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,949 6 7	By Investments (at cost):—	
		£1,308 London and North Eastern Railway 4% First Guaranteed Stock...	1,744 3 11
		£100 London County 3½% Consolidated Stock (1929 or after)	101 8 6
		£250 New South Wales 4% Stock (1942–62) ...	251 6 0
		£100 3½% War Stock (1925–28)	94 8 8
		£100 5% War Stock (1929–47)	95 0 0
		£381 15s. 1d. 4% Funding Loan (1960–90) ...	300 0 0
		£200 5% National War Bonds (1928)	211 11 0
		£200 Conversion Stock 3½% (1961 or after) ...	151 8 6
	£2,949 6 7		£2,949 6 7

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Grant made in 1925	107 0 0	By Balance (as per last Account)	109 5 10
„ Balance carried to Balance Sheet *	111 18 7	„ Dividends received in 1925	106 7 0
		„ Interest do. do.	3 5 9
	£218 18 7		£218 18 7

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,700 0 0	By Investment (at cost):—	
		£2,000 5% War Stock (1929–47)...	1,700 0 0
	£1,700 0 0		£1,700 0 0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Grants made in 1925	25 0 0	By Balance (as per last Account)	100 0 0
„ Balance carried to Balance Sheet *	175 0 0	„ Dividends received in 1925	100 0 0
	£200 0 0		£200 0 0

* Included in the total of £468 11s. 1d. shown on the Liabilities side of the Balance Sheet.

THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1925.

Dr. EXPENDITURE.

		£ s. d.
To Grants	£1,199 5 1	
Less previous Grant refunded	2 0 0	
		1,197 5 1
„ Printing, Stationery, Bank Charges, Postage, etc.		24 14 6
„ Unexpended Balance carried to Balance Sheet		491 2 1
		£1,713 1 8

INCOME. **Cr.**

	£ s. d.
By Dividends on Investments	493 16 5
„ Interest	13 1 8
„ Annual Subscriptions	327 0 0
„ Donations of £5 and over	411 0 2
„ Donations under £5	468 3 5
	£1,713 1 8

BALANCE SHEET, 31ST DECEMBER, 1925.

Dr. LIABILITIES.

		£ s. d.
To Capital Account :—		
As per last Balance Sheet	£9,969 11 3	
Donation to Capital in 1925	35 0 0	
		10,004 11 3
„ Income and Expenditure Account :—		
As per last Balance Sheet	£1,889 7 5	
Unexpended Balance in 1925	491 2 1	
		2,380 9 6
„ Sundry Creditors		8 8 0
		£12,393 8 9

ASSETS. **Cr.**

		£ s. d.
By Investments (Capital), at cost :—		
£961 7s. 7d. Cape of Good Hope 3 % Stock (1933–43)		950 0 0
£593 1s. 7d. New South Wales 3 % Stock (1935)		600 0 0
£420 London and North Eastern Railway 4 % First Preference Stock		503 18 3
£450 London, Midland and Scottish Railway 4 % Debenture Stock		551 0 9
£750 East Indian Railway 3½ % Debenture Stock		737 18 0
£300 London, Midland and Scottish Railway 4 % Guaranteed Stock		333 11 6
£500 New Zealand 3½ % Stock (1940)		486 18 6
£500 Canada 3½ % Stock (1930–50)		478 16 0
£1,161 4s. 3d. 5 % War Stock (1929–47)		1,102 6 6
£350 New South Wales 4 % Stock (1942–62)		336 18 6
£200 3½ % War Stock (1925–28)		188 17 3
£2,128 8s. 6d. 4 % Funding Stock (1960–90)		1,624 2 0
£2,000 5 % National War Bonds (1928)		2,110 4 0
		10,004 11 3
„ Investments (Income) at cost :—		
£965 2s. 5 % War Stock (1929–47)	£967 19 3	
£1,365 3½ % Conversion Stock (1961)	1,030 14 9	
		1,998 14 0
„ Sundry Debtors		122 6 5
„ Cash :—		
At Bankers'	£253 19 5	
In hand	13 17 8	
		267 17 1
		£12,393 8 9

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Bankers. The Investments, which are stated at cost, are subject to depreciation.

JAS. ATTFIELD, F.C.A.,
Honorary Auditor.

21st April, 1926.

ADDITIONAL APPLICATIONS OF THE MAGNETIC DRUM PRINCIPLE.*

By N. W. McLachlan, D.Sc. (Eng.), Member.

(*Paper first received 20th October, and in final form 15th December, 1925.*)

Summary.

Further applications of the magnetic drum principle using the magneto-cohesion effect described in a former paper are treated in detail. A description is given of a new form of siphon recorder, with a very small transit time, for high-speed reception on commercial circuits (beam stations). The shoe of the recorder is of special construction and the operating force for a current of 4 mA is about 4 lb., which is extremely large for a recording instrument. Owing to the rapidity of motion of the siphon lever it is possible to secure legible tape records when atmospheric disturbances are neither too severe nor too frequent. The procedure adopted in reading and transcribing messages at the central receiving station is given. Other applications of the magnetic drum principle to a delayed-action relay and to the checking of clocks by wireless signals are described. The thermionic valve circuits associated with the various devices are discussed and portrayed diagrammatically.

Table of Contents.

1. Introduction.

The principle underlying the operation of the apparatus described herein has been outlined previously.† Instruments identical in design with that used in the Institution Lecture Theatre to receive high-speed telegraphic signals from Paris (UFP) in April, 1923, are in service at sea and on shore and have proved absolutely reliable. Even after 10 000 hours' running the cast-iron rings on the drum are true to a small fraction of a mil. The life of a shoe is at least 4 000 hours when working at 100 words per min., the corresponding drum speed being about 150 r.p.m. The life is prolonged by having good alignment so that the toe of the shoe is on the crown of the drum when the relay tongue rests on the spacing stop and the line of pull is tangential to or passes slightly above the drum at this point. Under these conditions the tension required on the back spring is very slight and the normal pressure between shoe and rings is almost entirely due to the effect of the magnetizing current. Of course if comparatively large currents are used, say from 5 to 8 mA, or when working double current if the drum is not demagnetized during spacing (due to the polarization exceeding the signal magnetization or vice versa), the life of the shoe will be reduced.

2. Relay Classification.

Electromagnetic relays can be divided broadly into two types: (1) Those in which the energy of the incoming signal is expended, (*a*) in moving the tongue from one stop to another, this being represented by $W = \int mvdv = \int Fdx = \int eidt$, where m = equivalent mass, v = velocity, F = force, x = distance, i = current and e is the back E.M.F. due to the motion of the armature; (*b*) in energizing the magnetic circuit by the current in the coil, this being represented by $\frac{1}{2}Li^2$ + (mutual energy-changes) + (magnetization losses due to hysteresis and eddy currents); * (*c*) in the continuous generation of heat due to the current in the winding, this being $\int i^2rdt$. (2) Those relays in which the incoming signal supplies the energy for (*b*) and (*c*), that for (*a*) being obtained from an external source. Assuming the signal energy to be equal for both types of relay, it is manifestly clear that (*b*) and (*c*) can either individually or collectively be greater for the second than for the first type. Moreover, the degree of magnetization can be greater for the second type. The latter condition is usually concomitant with a larger operating force, so that a relay of the second class will, for the same energy input and equal moving masses, be more rapid in its action and the pressure at the contacts will be firmer than for a relay of the first class. Put in another way, the energy input for equal performance at any given speed of reception is less for a relay of class (2) than for a relay of class (1). Viewing the situation broadly, the second type can be regarded as belonging to the "trigger" denomination.† Taking a case in point, there is the magnetic drum type of relay in which the signal energy is expended entirely in (*b*) and (*c*) [chiefly in dissipation of heat, excepting at high speeds of operation where (*b*) is a larger proportion of the total than at, say, 100 words per min.] to cause a force between the revolving drum and the shoe. There is no back E.M.F. due to the motion of the shoe, excepting that due to hysteresis and eddy currents, which is relatively small, and the magneto-cohesion effect yields a manifold amplification.

The magnetic drum variety possesses the advantage

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1923, vol. 61, p. 907.

* In addition to $\frac{1}{2}Li^2$ there are mutual energy variations due to the armature being in the magnetic field of magnet and field coils, just as there are mutual effects between two coupled electrical circuits.

† The Piedfort relay is also in this class (see *Journal I.E.E.*, 1923, vol. 61, p. 926).

that for the same energy input, the ratio (torque/moment of inertia) is much greater than that for a relay of class (1), thereby ensuring a reduced transit time and a sure contact. There is, of course, the question of revolving the drum continuously, but this is a simple matter at a radio or other central station. In some forms of relay in class (1) a large polarizing current is essential for the electromagnet. The energy absorbed by the winding of the electromagnet is usually equal to or greater than that required by the motor which turns the drum.

It is of interest to observe that the sensitivity of both classes of relay would be appreciably augmented if the ohmic resistance of the winding could be reduced to, say, one-tenth of its present value by the aid of wire of higher conductivity. Also the employment of suitable magnetic material of lower hysteresis loss, reluctivity and coercivity would assist admirably in improving relays in general.

3. Small Drum Recorders.

To meet special requirements a new type of recorder with a drum of smaller dimensions than that used on the standard pattern has been developed. This type will be used for high-speed reception in the beam stations of the Marconi Co. The reduced dimensions give a shorter magnetic path through he shoe, and for a fixed number of ampere-turns the pull with a shoe of definite size is a good deal larger than that on the standard,* although in this respect the state and nature of the drum and shoe surfaces play an important part. The peripheral speed of the small drum appreciably exceeds that of the standard, and the surfaces of the cast-iron rings during operation are somewhat different in the two cases. In general there is a brownish deposit on the small drums and this is usually accompanied by large operating forces. The general arrangement is given in Figs. 1A and 1B, the

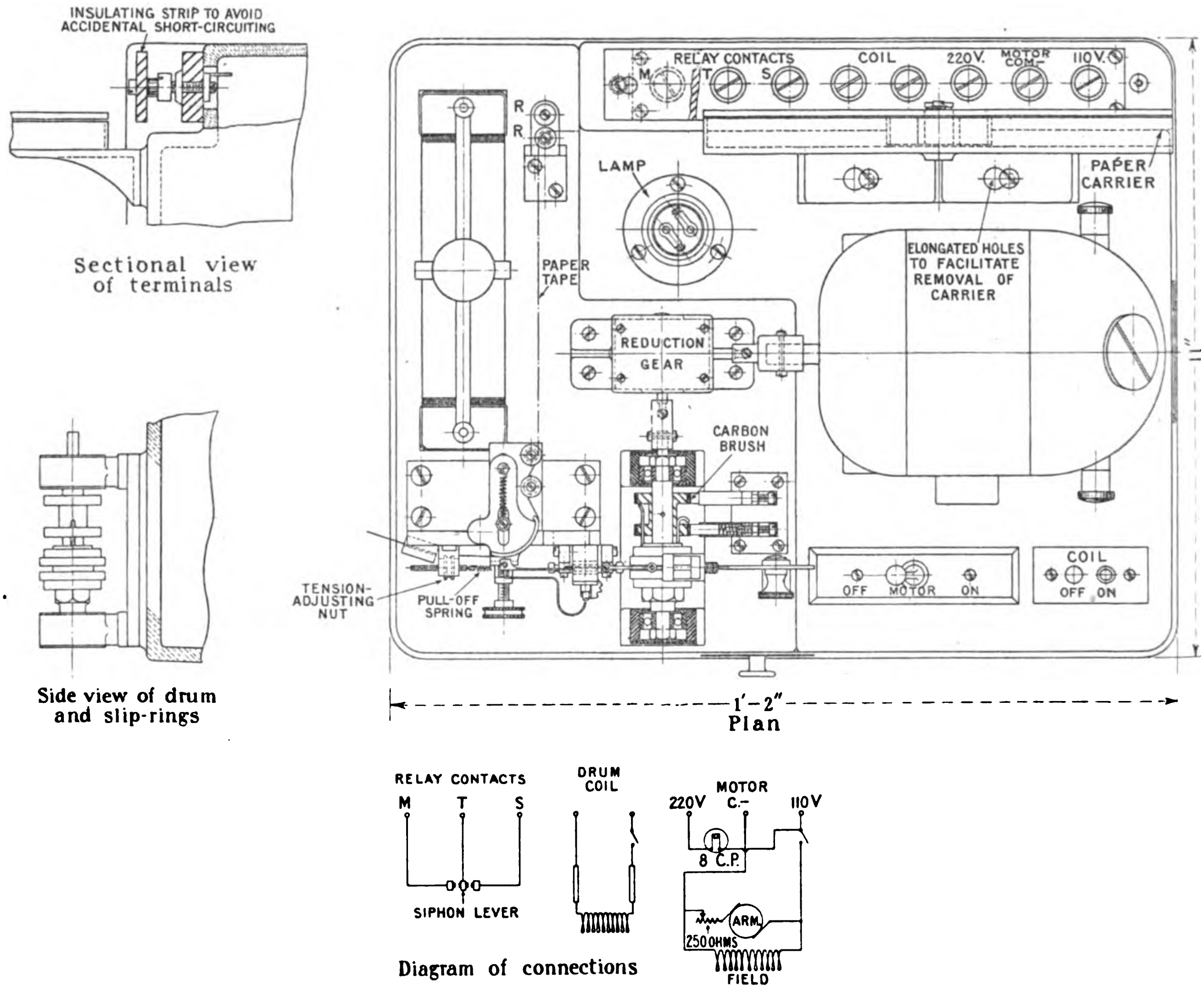

Fig. 1A.—General plan arrangement of magnetic drum recorder (transoceanic pattern) with vertical paper drive. The inkwell is not shown.

* See *Journal I.E.E.*, 1923, vol. 61, p. 904, Fig. 1.

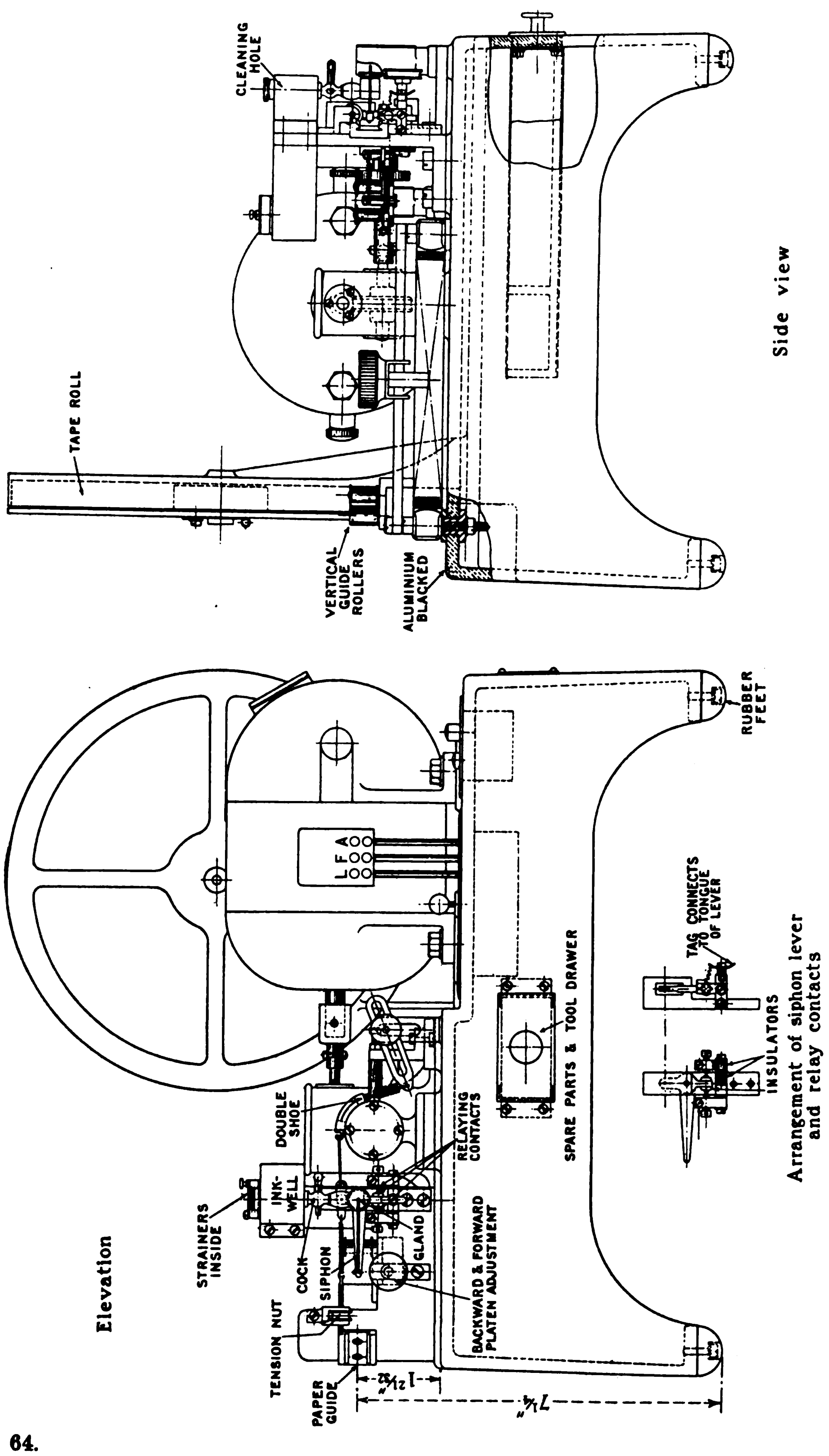

Fig. 1B.—Elevation of instrument shown in Fig. 1A, and arrangement of siphon lever and relay contacts.

former also showing a cross-section of a small drum, from which the construction will be clearly seen. The bobbin is of either ebonite or stabilite wound with about 3 000 turns of either 46 s.s.c. or 48 d.s.c. wire. The larger wire is usually preferable owing to the smaller resistance which measures about 600 ohms, whereas with 48 d.s.c. wire the resistance is double this value. The sensitivity obtained with these windings is ample for recording purposes, but it can be increased by winding the bobbin very carefully with the best quality possibility of short-circuiting of turns the bobbin may be made of bakelite. The bobbin is fixed on a brass former which prevents the flanges from bulging out sideways during winding. The whole is impregnated with fluid bakelite and subjected to the necessary heat treatment. The brass former prevents distortion during the latter process.

The pull and flux curves for the drum of Fig. 1 are given in Fig. 2, and similar curves for the standard recorder have been added for the purpose of com-

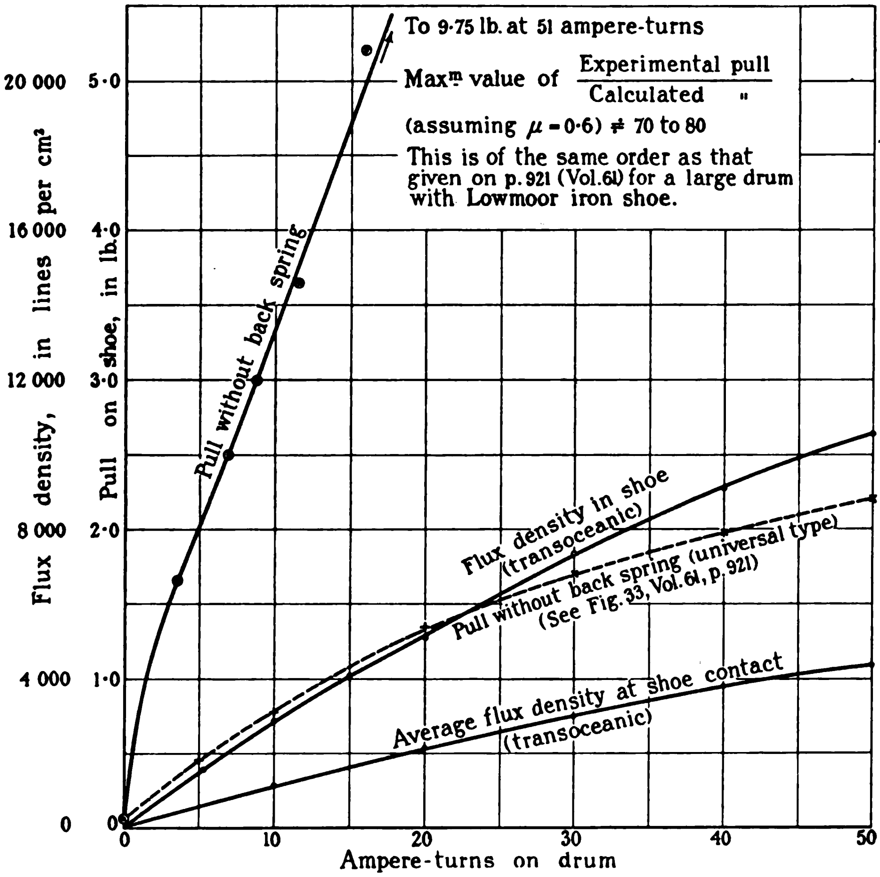

Fig. 2.—Pull and flux curves for small magnetic drum recorder with two-part steel shoe.

Cross-sectional area of first part of shoe	= 0·17 cm²
Cross-sectional area of second part of shoe	= 0·17 cm²
Total	= 0·34 cm²
Total curved surface area	= 0·83 cm²
Width of cast-iron rings	= 0·39 cm
Turns on drum (in this particular case)	= 3 500 (No. 48 d.s.c. wire).

No. 48 S.W.G. enamelled wire. The number of turns will now be approximately thrice that with silk-covered wire of the same gauge, so that only one-third the current will be required to produce the same force between drum and shoe. The resistance is augmented considerably so that although the current sensitivity is increased the energy sensitivity is decreased. This, however, may be a requisite feature where valve circuit operation pertains. The insulation between adjacent turns of enamelled wire will not withstand a large voltage, and to ensure reliability and minimize the parison. The small drum is obviously much more sensitive, and care must be exercised in designing small drum recorders that the working forces are not too large. Excessive forces mean considerable wear and tear on the mechanism, and the frequent occurrence of mechanical fractures. When using the circuit depicted in Fig. 3 there is a large initial charging current to the condenser when the tongue meets stop M, and this current may be many times the steady current. The initial rate of rise of this current is E/L, where E = the E.M.F. of the battery and L the inductance of

the drum. With 100 volts and a coil of 3 000 turns the initial magnetization grows at the rate of 60 000 ampere-turns per second. Moreover, the initial force is greater than the steady force and may reach a value of 6 lb.

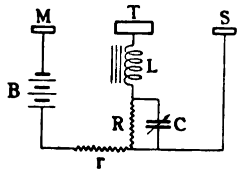

FIG. 3.—Circuit for working magnetic drum relay off the contacts of a relay or another drum recorder.

M = marking stop of relay.
T = tongue of relay.
S = spacing or back stop of relay.
B = battery (50 to 100 volts).
L = coil of recorder.
R = resistance (20 000 ohms).
C = variable condenser (0·5 to 1 μF).
r = safety resistance (200 ohms).

or more, which is enormous for a recording instrument. Thus the transit time is appreciably smaller than that of the standard recorder, and when the stops are open fairly wide the action of the instrument—with appropriate drum speed—is accompanied by a series of hammer-blows. The steady current which follows the charge to the condenser must be sufficient to prevent the lever arm bouncing off the marking contact. The marking transit time, especially when the amplitude of the siphon point is large, say ¼ in., can be controlled by varying the speed of the drum, and it is interesting to hear the blows weakening and to see the transverse lines becoming more inclined to the vertical as the speed is reduced. A point is usually reached when the motor torque is insufficient to drive the drum. The gear ratio for the drum is 5 : 1 so that with a motor working at 3 000 r.p.m. the drum speed is 600 r.p.m. For an amplitude of 0·0875 in. on the tape the peripheral speed is then just adequate to obtain as large a final velocity of the tracing point as the working force can cause with an operating current of 4 to 5 mA. For continuous operation a drum speed of this magnitude would cause heating and undue wear as well as violent treatment of the recording mechanism. It is arranged, therefore, that the motor speed shall not exceed a certain limit and the speed can be reduced below this limit by means of a rheostat. In this way the marking transit time of the siphon lever is controlled. The siphon mechanism and shoe are designed to give minimum transit time. The condition to be fulfilled is that the moment of inertia of the siphon mechanism* shall be equal to that of the shoe, and that the total moment of inertia shall be as small as is compatible with mechanical strength and reliability.

The small drum instruments are useful for measuring time intervals between successive electrical or other impulses which can be converted to electrical form. Knowing the speed of the travelling paper-tape, the time interval is a function of the distance between vertical marks on the tape. The apparatus is also of value for circuits where atmospherics are troublesome, e.g. long-wave transoceanic circuits. A sample of tape obtained from a long-wave circuit is shown in Fig. 4. This is similar in appearance to that obtained with the standard type of recorder when the drum speed is about 250 r.p.m. and the tape moves slowly. There is little difference in the appearance of the tape from the two types of instrument unless the duration of the disturbance is very short, and the balance is in favour of the small drum. This aspect of the subject is treated below under "Transit times."

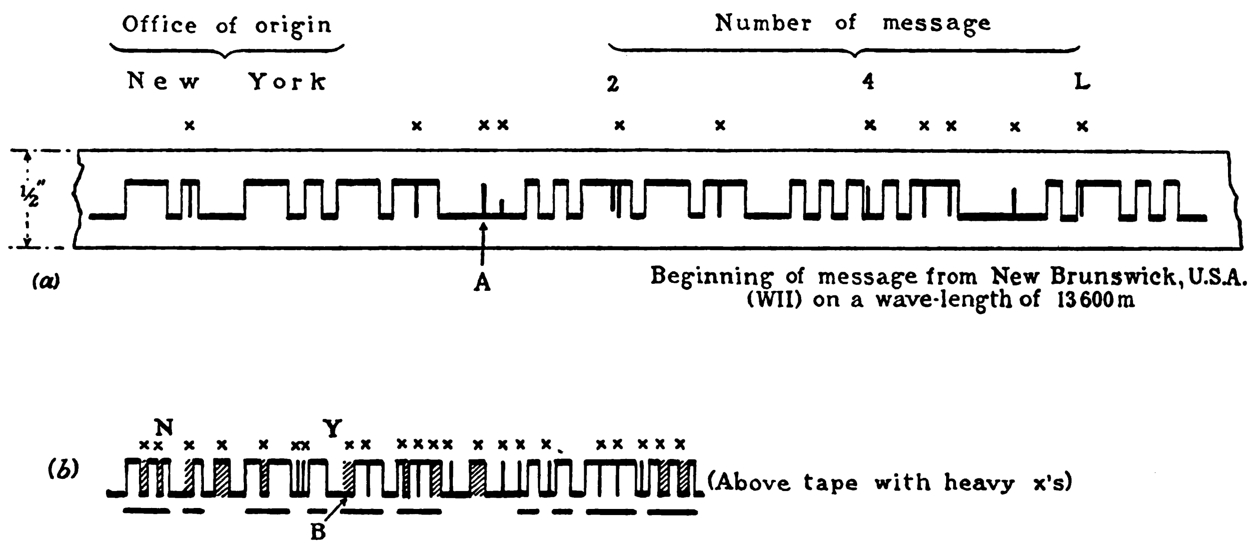

FIG. 4.—Sample of tape taken at Chelmsford (June, 1923) with magnetic drum recorder by the aid of the circuit portrayed in Fig. 6.

The transmission was automatic at from 20 to 30 words per minute. Atmospherics were not severe or many of the thin vertical lines would have resolved themselves into areas as shown in (*b*). Occasionally the end of the siphon did not make a complete transit owing to the short duration of the X in the receiving circuit, i.e. weak X's. The effect during marking and during spacing is clearly exhibited. (*a*) Shows the original tape, whilst (*b*) indicates the effect of severe atmospherics which render the record unreadable.

* *Journal I.E.E.*, 1923, vol. 61, p. 923.

The small drum apparatus is exhibited in Fig. 1. The construction is different from the standard shown in Vol. 61, p. 904 of the *Journal*. Both instruments are mounted on dull black aluminium bases and the finish is gold-lacquer-black. The shoe of the small drum is in two parts held by clamping strips, or preferably cut from a solid ring and spaced at an angle of about 40° to 80°. This construction is imperative owing to the larger curvature of the drum. The natural tendency of a single shoe riding on a drum of large curvature (small diameter) is to move tangentially to the crown. This actually happens after a single shoe has been in use for 15 to 20 minutes. Moreover, the heel of the shoe rides off the drum instead of adhering to it, and the two-part construction was designed to obviate this trouble.

There is no automatic tape feed as on the standard instrument. The paper roll is placed in a vertical position, thus economizing in space, and the framework in which the roll is contained is readily removable either for transport purposes or for the rapid insertion of a new roll. The plane of the tape issuing from the roll is horizontal and this is passed between two vertical rollers RR, which serve to turn it into a vertical plane. It then passes over a curved platen near the crown of which*—assuming the paper to travel from right to left—the siphon point operates, and thence to a vertical slotted guide through which it is drawn by a separate paper puller. The inking arrangement is unique. In order to avoid bending the siphon during operation, the axis of rotation must coincide with that of the siphon lever. To attain this object a cock is let into the base of the inkwell and to the lower end is fixed a gland with a rubber disc as packing. The centre of the gland is coaxial with the siphon. The feed is therefore of a gravitational nature, and during idle periods the cock must be shut to prevent ink flowing over the instrument. For coping with blocked siphons, a special siphon syringe is supplied with both types of magnetic drum instrument. The barrel is filled with methylated spirit and the upper end of the siphon is removed from the gland on the recorder and fitted to an identical gland at the top of the syringe. A gentle pressure on the piston serves to discharge sufficient methylated spirit through the siphon to clean it out thoroughly. Precautions are taken as far as possible to prevent sediment getting into the inkwell, by fitting a strainer. The ink feed is extremely regular and can be controlled in a degree by the pressure of the siphon point on the paper and by closing the ink inlet at the top of the well. The siphon arm is longer than that on the standard, because the mechanical construction required for vertical instead of horizontal motion involves the line of pull of the shoe being further away from the central axis about which the siphon mechanism turns. The lever ratio, however, is still 4 : 1 and the moments of inertia are such as to give the tracing point its maximum velocity for any given force on the shoe, the mechanical strength of the mechanism being adequate to withstand the shocks due to impact on the stops.† These are shown in Fig. 1 and are used where the incoming signals are to be relayed to a land line or to a printing machine. The instrument is fitted with relay contacts if required.

* The siphon point should be about $\frac{1}{16}$ in. to the right of the crown line.
† *Journal I.E.E.*, 1923, vol. 61, p. 923.

The aluminium base which rests on hemispherical rubber feet is apparently rather high, but this is necessitated by the design of tape puller to be used conjointly. Otherwise the height could have been reduced several inches. A drawer for spare parts is situated at the middle of the base and this contains the syringe, spare shoes, springs, siphons, etc., and some small tools. A $\frac{1}{8}$-h.p. motor arranged for 110 or 220 volts d.c. drives the drum through a 5 : 1 acme thread gear. The speed of the motor is controlled by a rheostat and is limited to 2 000 r.p.m.

In transcribing low-speed tape the usual practice is for the operator to sit with telephones on his head in front of a typewriter. The paper tape is drawn past the siphon point of the recorder by a tape puller consisting of a variable-speed shunt-wound motor coupled to pulleys via a worm reducing gear. The operator reads the signals both aurally and optically, and to assist in the latter operation it is preferable to run the tape in a vertical plane. The operator can then get a clear view of the tape from the paper puller to the siphon point, the motion of which can be followed if desired. This procedure is known as the "audio-cum-slip" method. There are in general two tape pullers, (*a*) one immediately before the typewriter, and (*b*) one after the typewriter. This enables the first puller to cause a paper travel suitable for high-speed reception, whilst the second puller is adjusted to a speed suitable for direct transcription on the typewriter. The untranscribed tape accumulates on the operator's right hand and is either dealt with in due course or handed to another transcriber, according to the conditions of reception and service. Under the latter circumstances, i.e. high-speed reception, the audio-cum-slip arrangement is suspended.

The features of small drum recorders are as follows:

(1) For a given current the operating forces are larger than the standard.
(2) They are specially suited for recording on circuits where atmospherics are prevalent, owing to the small transit time and the independent control of the drum and tape speeds.
(3) The transit time can be varied.

4. Transit Times of Recorders.

This is a subject which requires careful consideration on low-speed circuits where atmospherics are prevalent, or on high-speed circuits where characters follow one another in rapid succession. At the moment, atmospherics worry the long-wave circuits most of all. It has been shown elsewhere* how the legibility of recorded signals can be enhanced when atmospherics are neither too strong nor too frequent to upset recording altogether. For this purpose the recorder must move with great rapidity.

In measuring the transit times of the recorders for marking and spacing, the amplitude was adjusted to $\frac{1}{8}$ in. and the recorder actuated in conjunction with a

* N. W. McLachlan: *Journal I.E.E.*, 1924, vol. 62, p. 353.

rapidly responding electric circuit. Dots of known frequency were sent by a local Wheatstone transmitter, the marking and spacing being equal in duration. The paper tape was drawn past the siphon point at a speed concomitant with a record taken at 2 500 words per min. so that a dot at a sending speed of 25 words per min. was about 6 in. long. Care was taken to avoid undue paper friction, and to ensure an adequate supply of ink a gentle air pressure was applied to the feed. A typical dot at a lower paper speed than that cited above is shown in Fig. 5. The initial and final for an a.c.-d.c. converter of the type shown in Fig. 9. The current in each coil was approximately 3 mA. The drum speed was insufficient to give the shoe its greatest velocity and hence the end of the transit curve was linear. The marking transit time with adequate drum velocity is 0·0018 sec.

The recorder was operated under normal valve circuit conditions using 1 coil only with about 4·0 mA (see Fig. 6). The marking transit time with adequate drum speed is 0·0016 sec. By suitable design the time can be reduced below this figure to about 0·0013 sec.,

FIG. 5.—Magnetic drum recorder (transoceanic type). Dot at low speed ; paper speed equivalent to 1 800 words per min.

transit curves are approximately parabolic. If the force on the mechanism and the paper speed are constant, the motion of the tracing point relative to the paper is identical with that of a particle projected horizontally and falling freely under the influence of a constant gravitational attraction. In order to ensure this condition it is essential that the peripheral speed of the drum shall not be less than the speed at which the shoe would move when the mechanism reached the marking stop if acted upon freely by a force equal to that between drum and shoe. When the drum speed is less than this, the end of the transit curve is a straight line, for the shoe is no longer accelerated but is moving at a constant velocity equal to that of the drum.

Data concerning transit times and allied topics are given in Tables 1 to 4.

TABLE 1.

Standard or Universal Type with Tape Puller Incorporated.

Transit time (sec. $\times 10^{-3}$) for amplitude of 0·125 in. on tape.

Marking		Spacing	Total
Experiment	Calculation	Experiment	Experiment
2·3	2·2	3·1	5·4

TABLE 2.

Transoceanic Type with Separate Tape Puller.

Transit time (sec. $\times 10^{-3}$) for amplitude of 0·125 in. on tape.

Marking		Spacing	Total
Experiment	Calculation	Experiment	Experiment
2·0	1·9	2·0	4·0

The recorder was operated under normal receiving conditions, being situated in a valve circuit as used, but there is undue impulsive stress on the siphon mechanism.

From Tables 1 and 2 it will be seen that a fair agreement exists between the experimental and calculated values of the *marking* transit time. So far as the spacing transit time is concerned, calculation is out of the question without a knowledge of the time-lag of demagnetization. If this lag were negligible the process of computation would be identical with that for marking. There is reason, based on experimental evidence, to believe that it is not entirely negligible although the condenser-resistance combination can be varied over a fairly wide range without causing alteration in transit time of any practical importance. It will be appreciated that for any given working current the marking and spacing times can be made equal or otherwise by adjusting the pull-off or control spring, and that for a specified tension of the spring the marking

TABLE 3.

Torques and Moments of Inertia.

Instrument	Working torque marking	Moment of inertia (mass × sq. in.)	Angular acceleration $\frac{Fr}{I} = \ddot{\theta}$	Force / Mass	Equivalent mass of moving parts referred to line of action of force
	lb.-in.				lb.
Universal ..	0·25	0·00125	200	50	0·02
Transoceanic	1·0	0·005	200	100	0·02

TABLE 4.

Acceleration and Final Velocity of Tracing Point, assuming Drum Speed to give Shoe its Greatest Velocity, the travel of the point being 0·125 in.

Instrument	Acceleration of tracing point on marking	Final velocity at marking stop of tracing point
	ft./sec./sec.	ft./sec.
Universal ..	6 400 *	11·4
Transoceanic ..	8 000	12·8

* 200 times the acceleration due to gravity.

transit time can be altered by changing the value of the working current.

In the foregoing remarks the rate of rise of current in the recorder coil has been tacitly ignored. With a comparatively large inductance (several henrys) the time taken for the current to attain a working value must be considered. In the universal or standard type of instrument this amounts to a duration of the order of 0·0004 sec., whilst in the transoceanic or small drum type it is slightly less. Such a value is not of appreciable moment under the present system of ink marking. If, however, an optical arrangement were employed in which the motion of the lever was, say, 1/100th of the figures already quoted, the transit time under the action of the force at full current value would be less than 0·0004 sec. This would necessitate a modification in the design, e.g. a much smaller inductance to enhance the rate of rise of current.

5. Recording through Atmospherics.

When a time/displacement curve of the transmitter modulation is plotted, the result is a series of morse characters in rectangular formation—neglecting of course the initial and final lag due to electromagnetic inertia. In recording incoming signals of this nature it seems a reasonable—but not an exclusive—hypothesis that, apart from atmospheric disturbances and jamming, the time/displacement curve of the transmitter should be reproduced on the paper slip or tape at the receiver. It is known, however, that the signal profile is modified by low-decrement circuits at both transmitter and receiver—principally the latter—and after protracted filtration the curves "enveloping" the oscillations of either radio or audio frequency (according as the filtering is done at radio or audio frequency or both) are no longer of rectangular formation. The shapes of the growth and decay envelopes depend upon the number and the decrements of the circuits in cascade. Prior to recording the incoming signals of audio frequency, it is usual to rectify and smooth the oscillations in order to secure a unidirectional component. The envelope is modified in this conversion process from alternating to direct current, and when the signals are applied to a power or recording valve set to its lower rectifying point an additional alteration in shape is accomplished, especially if the valve is given an unusually large negative grid bias. The latter expedient is a useful artifice in squaring up the signal profile. In what follows it will be assumed, unless otherwise stated, that the envelope of the signal and interfering voltages applied to the recording valve is of rectangular profile, also that the transmission is automatic, thereby preserving uniformity of the characters. This latter is the usual practice in commercial work.

In the preceding Section, incidental reference was made to the influence of atmospherics on the tape record. It is intended to show what conditions must be fulfilled so that atmospherics do not make the record illegible. The visual condition is simply that the area of the marking which represents an atmospheric must be small in comparison with that of a dot, a dash or a space. Also the atmospheric scribings must not be too frequent to fill up the characters. These points are illustrated diagrammatically in Fig. 4. Apart from the signal profile there are two electrical issues with which we are concerned: (1) The rapidity of response of the recorder, and (2) the duration in the receiving circuit of (*a*) the signal, and (*b*) an atmospheric. Firstly, if the time interval between the initial application of the voltage to the grid of the recording valve and the arrival of the siphon point at the marking position is small compared with the duration of a dot; secondly, if the time interval between the initial decaying of the applied voltage and the arrival of the siphon point at the spacing position is small compared with the duration of a dot, the marking on the tape will be of rectangular formation (unless the tape speed be excessive) and the space/time curve of the siphon point will closely resemble that of the voltage/time curve associated with the Wheatstone contacts at the transmitting station. Where atmospherics are concerned the required condition is that the siphon of the recorder shall make a complete to-and-fro transit within a limited time interval, depending on the tape speed and the speed of transmission. There are two salient cases to be examined: (*a*) When atmospherics occur during spacing, and (*b*) when atmospherics occur during marking. During spacing little or no *signal* voltage is applied to the recording valve, but in general there will be a decaying current in the aerial and its associated circuits. The effect of an atmospheric will depend upon the phase of the signal E.M.F. in the aerial at the initiation of the disturbance and also upon its (the X's) wave-form. If the aerial current is adequately augmented the atmospheric will be registered on the tape. The siphon point will make an excursion across the tape and back to the base line or spacing position. This is portrayed at A in Fig. 4. During marking the aerial current will either be growing or decaying or be sensibly constant. The influence of an atmospheric will again depend on its phase and wave-form with reference to the signal. If the aerial current due to the signal is a small fraction of the maximum and the atmospheric is strong enough or suitable as regards phase and intensity, the aerial current will be augmented sufficiently to cause marking on the tape. On the other hand it may practically de-energize the aerial and delay the initiation of the morse character, thus making a prospective dash more like a slightly elongated dot (see B in Fig. 4 (*b*). When the signal current has attained its full working value the same additive and subtractive effects can be obtained from X's. Augmented aerial current during marking due to an atmospheric yields no visible result on an instrument which functions between stops, but an adequate decrease in current is accompanied by a motion of the siphon to the base line and back to the marking position. These remarks are illuminated by the tape record reproduced in Fig. 4. This was secured by aid of the circuit sketched in Fig. 6. The legibility of the tape is enhanced appreciably if the siphon point is oval, the major axis being at 90° to the motion of the tape. This gives thin vertical and thick horizontal strokes.

Passing on to the second point, which concerns the rapidity of response of the complete receiving circuit, the condition to be satisfied is that the duration of the

voltage applied to the grid of the power valve due to an X shall be small compared with that due to incoming characters in the morse code. The maximum value of the voltage is not of material importance, merely its duration above a working value, although in virtue of the receiving circuit the two are usually associated. This necessitates a receiving circuit in which the decay reduced so that the areas will become smaller in proportion to the characters and, furthermore, the speed of the paper tape can be decreased, thus tending to reduce the areas to vertical strokes. In practice this condition generally holds down to a certain minimum speed below which it is more economical and satisfactory to read the messages aurally. Where speeds vary over a wide

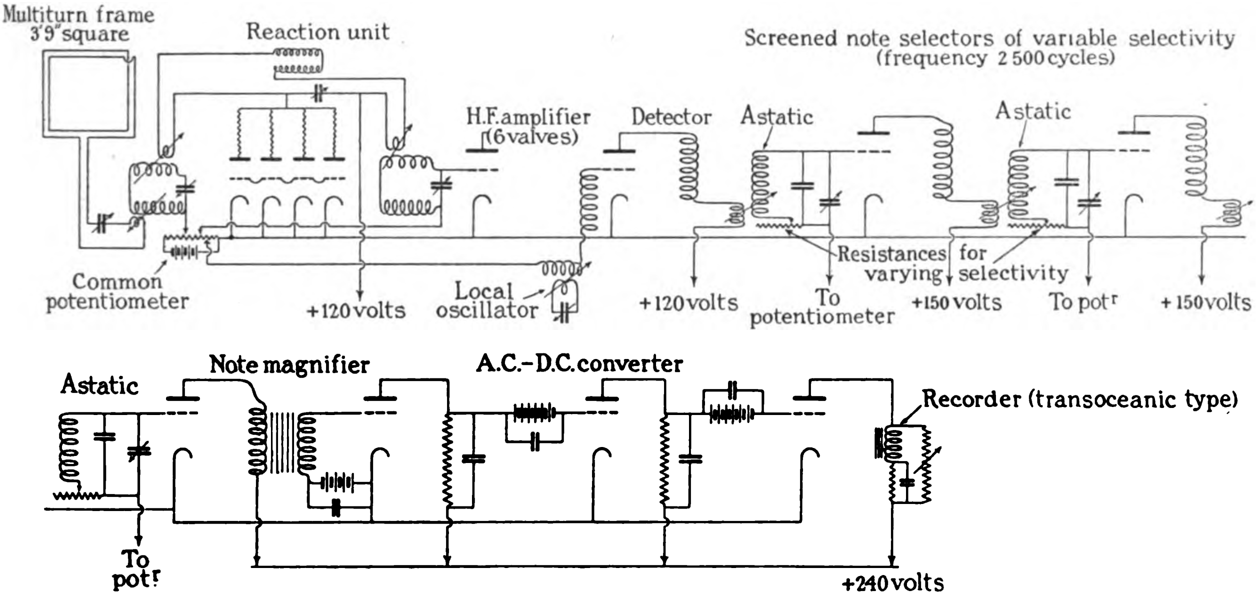

FIG. 6.—Circuit used to obtain tape of Fig. 4 from New Brunswick (WII).

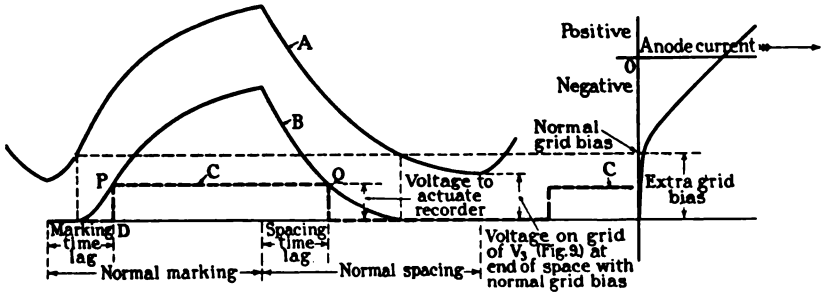

FIG. 7.—Diagram illustrating the effect of using extra grid bias on the recorder valve V_3 of Fig. 9.

A continuous marking is transformed by the recorder into morse characters of rectangular formation, the time displacement curve of which is shifted forward, i.e. lags. In practice the result is legibility, since the profile of the signal is akin to that of Fig. 4 (*a*). No allowance has been made for the influence of grid current at the power valve with strong signals. This in itself tends to round off the points of curves A and B, since it is equivalent to a coupling resistance between V_2 and V_3 which decreases as the signal increases.

A = Voltage applied to grid of V_3 of Fig 9. In the absence of extra grid bias the current through the recorder is determined by this curve. Since the current is always above the working value, the record is a continuous horizontal line, i.e. the morse characters merge together.

B = net voltage applied between grid and filament of V_3, i.e. curve A minus the extra grid bias. This is approximately the same shape as the voltage applied across the recorder and its shunted resistance combination. Owing to the inductance and condenser the current curve is modified. The current to actuate the recorder is determined by the tension of the pull-off spring.

C = representation of marking on the tape.

period is reasonably proportioned with respect to the length of a dot. There is a value of decay period, according to the speed of sending, the number or frequency of occurrence of the atmospherics and their strength relative to the signal, beyond which the tape becomes illegible due to the formation of relatively large areas (due to the X's). In order to secure legibility, the speed of sending can be range, according to the conditions of reception, it is imperative to have a receiving circuit of variable selectivity. When a series of tuned circuits are used, this variation can be secured by altering the couplings or by manipulating variable resistances in the *LC* components (see Fig. 6). A master control operating all circuits simultaneously is obviously preferable.

The problem of recording highly rounded signals due

to low-resistance circuits has been raised elsewhere.* It has been established in practice by having two rectifiers in cascade as in Fig. 9. By giving one or both an extra negative bias, *in the absence of atmospheric and other disturbing factors*, recording can be accomplished when signals are well-nigh aurally unreadable. A third rectifier helps still further and in that case the negative bias on the other two can be reduced. Conditions free from interference are seldom enjoyed, but even so this simple artifice is by no means to be despised.

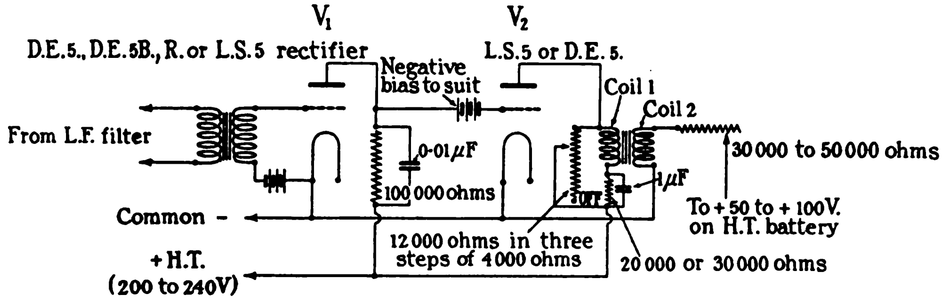

FIG. 8.

The effect of a large negative bias on valve V_3 of Fig. 9 is illustrated clearly in Fig. 7. At P the voltage applied between the grid and filament of V_3 is large enough to actuate the recorder and from P to Q marking is registered, the siphon then falling back to the base line. The profile of curve B between P and Q is immaterial, provided the ordinates exceed PD. So far as the magnetic drum and other fixed-stop instruments are concerned, the behaviour is equivalent to

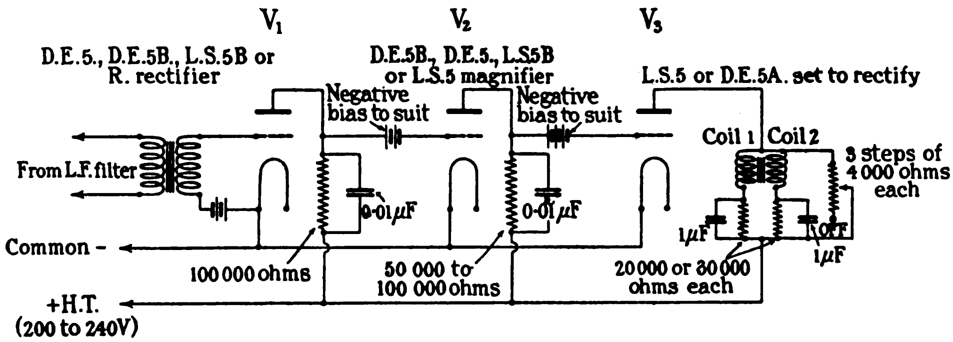

FIG. 9.

that from an input voltage of approximately the rectangular formation of curve C.

6. A.C.-D.C. Converter Circuits.

Several valve circuits used for the direct recording of radio signals were given in the first paper.† For commercial operation it is usually advisable to avoid "trigger" circuits, and moreover the arrangements are devoid of awkward adjustments, being straightforward and affording the desired degree of amplification. There are two main classes into which valve recording circuits may be divided: (*a*) Single current, and (*b*) double current. In general the second class (*b*) has one valve more than the first class, this being required to give the reverse current. The magnetic drum recorder requires a reverse current to cause rapid demagnetization, but it can be obtained automatically by the discharge of a condenser,* thus permitting simplification of the circuits and dispensing with the extra valve for spacing. In general it is preferable to work from common anode and filament current supply sources, and the diagrams cater for this condition to be fulfilled. The function of the recorder circuit is to convert the alternating currents of beat (audio) frequency, usually from 1 500 to 2 500 cycles, into unidirectional pulses whose durations are those of the morse dots and dashes. During the conversion or smoothing process there is usually a certain degree of amplification. For good recording at a speed of 100 words per min. the potential difference between the grid and filament of the power valve during a morse character should not be less than 40 volts. The power valve should have a low internal resistance so that a reasonable proportion of the anode supply voltage is expended on the recorder and its associated apparatus. Suitable valves are D.E.5, D.E.5A, L.S.5, and L.S.5A. The anode supply voltage should not be less than 200.

Fig. 8 shows a simple converter unit consisting of rectifying and power valves. Smoothing is effected by the condenser in the anode circuit of the rectifying valve. During idle periods a current flows through one of the recorder coils via the power valve. The

* *Experimental Wireless*, 1924 vol. 1, p. 623. The diagram on page 625 is not quite correct.
† Loc. cit.

* Loc cit., p. 907

second coil is connected to a tapping point on the anode supply, and the current is adjusted by a variable resistance until it is approximately equal to that in the first coil, but the magnetizations are opposed. Moreover, there is little or no pull on the recording mechanism. When a signal E.M.F. is applied to the rectifier the anode potential falls, and the potential of the grid of the power valve falls by an equal amount, thus reducing the current through coil 1 practically to zero. This leaves the magnetization due to the current in coil 2 free to actuate the recorder. Moreover, the operation of the recorder depends upon a falling current through the power valve.

The next circuit is illustrated in Fig. 9. Here we have a circuit akin to that of Fig. 8, except that there is a valve inserted between the rectifying and recording valves. This valve and its associated condenser-resistance in the anode circuit not only gives additional magnification and smoothing, but serves to make the recorder valve operate on a *rising* current. In this case both coils of the recorder are used, which is an advantage.

Since the transoceanic type of recorder has only one coil it can be used with the circuit of Fig. 9, but not with that of Fig. 8, unless of course the tape is read upside down, there being no polarizing current to invert it automatically as in the universal type.

7. Delayed-Action Relay.

In automatic calling-up or switching devices, which are really a form of remote control, it is sometimes desirable to introduce a peculiarity in the response of the system. This may take the form of a time-lag or delay in the ultimate action of the relay at the distant station where the receiving apparatus is installed. Such an action can be accomplished by the combination of some type of relay with a dashpot, thermostat or like device so that an uninterrupted signal has to be applied for a definite length of time to ring the call bell. As an example we may take the Marconi Company's wireless bell call-up device in which the transmitter is modulated by an audio frequency of about 1 500 cycles, and the selective circuit at the receiver is tuned to this note. Unless a delayed-action combination were installed, any strong nearby jamming station would actuate the call bell.

The magnetic drum principle can be applied readily to fulfil the double function of a relay and a delayed-action device. This is accomplished by passing the signal current through the operating coil on the drum and revolving the latter very slowly, say once every 30 to 60 minutes. In this way, during continuous signalling the shoe and the lever carrying the relay contacts move uniformly but very slowly from the "off" to the "on" position, i.e. from the spacing to the marking contact. With an intermittent signal, for instance morse jamming, the tongue of the relay dallies about the "off" contact. It is essential that this should occur, and the circuit must be arranged to respond rapidly to avoid a cumulative effect which would culminate in an excursion to the marking contact. The drum is identical in dimensions with the universal type, except that the bobbin is slightly deeper to accommodate 30 000 turns of No. 48 enamelled wire. The wire can be wound on a bakelite bobbin and bakelized as described in a preceding Section. No back spring is required for the shoe, since there is no tendency for the rear extremity to lift as in high-speed signalling. The drum is driven by either an electric or a clockwork motor. The advantage of the electric motor needs no comment, but it may be inconvenient in certain cases where an adequate power supply is not available. (A $\frac{1}{40}$ h.p. motor serves the purpose admirably.) Obviously it is necessary to have a large gear reduction to secure the low speed required for the drum motion. It is of interest to note that the drum speed is so low that the signal would require to be applied continuously for *over a century* to cause appreciable wear.

Apart from the fact that this delayed-action relay system is sensitive—the operating current is from

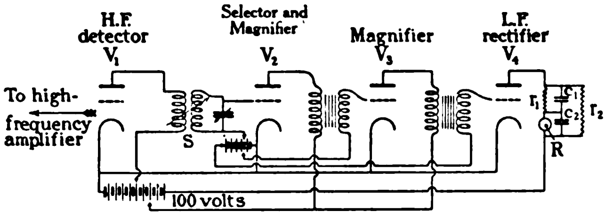

Fig. 10.

V_1 = H.F. detector.
V_2 = note-selector valve.
V_3 = magnifier.
V_4 = low-frequency rectifier.
R = drum relay.
r_1 = resistance (50 000 ohms).
C_1 = condenser (2 μF).
r_2 = resistance (30 000 ohms).
C_2 = condenser (0·02 μF).
S = tuned-note selector (1 000 to 2 000 cycles) loosely coupled.

If the signals are sufficiently strong, V_3 can be omitted. Suitable valves are V_2 = D.E.3, V_3 = D.E.3, V_4 = D.E.3B: to be mounted in shock-absorbing holders. The current supply to the filaments is very small with these valves.

As an alternative to the above circuit, valve V_3 may be coupled resistively to V_4 (V_3 may or may not be set to rectify). A condenser across the resistance is used to smooth the alternating current (the frequency of which is from 1 000 to 2 000 cycles) when V_3 is set to rectify. If V_3 is not set to rectify, the condenser is omitted.

0·3 to 0·5 mA—it possesses the advantage of being extremely flexible, because the time-lag can be varied over a wide range by altering the spacing between the stops and the speed of the drum. The variation depends upon conditions but can easily be arranged for any lag from 1 to 30 seconds. With a single thermostat or a dashpot, a 30 : 1 ratio would be quite impossible.

The relay is operated from any suitable receiving set capable of supplying signals of adequate strength. A satisfactory circuit with a note selector incorporated is portrayed in Fig. 10. This is connected direct to the terminals of any high-frequency amplifier. An air-cored coil of high impedance is connected in the anode circuit of the high-frequency detector valve. This coil is loosely coupled to an oscillatory circuit connected across the grid and filament of the valve V_2. The anode circuit of this valve contains the primary of an iron-cored 4 : 1, 6 : 1 or 8 : 1 transformer, according to the type of valve and the note frequency. The secondary of the transformer is connected to the grid and filament of the relay valve V_4 via valve V_3 and another transformer or a resistance. V_4 is set to the

rectifying point on its anode-current/grid-voltage characteristic. In the anode circuit of V_4 is situated the drum coil shunted by a small smoothing condenser which reduces the impedance of the circuit and thereby enhances the steady current during the signalling dash. The increase in steady current depends upon conditions, but on the average it is doubled due to the condenser across the drum. This will be more readily appreciated when it is realized that the inductance of the drum at 100 cycles is about 600 henrys. Taking a fundamental note frequency of 1 500 cycles, and assuming the drum inductance now to be 200 henrys, the inductive reactance alone is nearly 2 megohms, whereas that of a $0 \cdot 01\ \mu F$ condenser is only 1/200th of this value.

In series with the drum is a shunted condenser combination Cr_1, and the whole arrangement is paralleled by a resistance r_2. It has already been stated that there must be no cumulative effect due to a rapid succession of signals, and the Cr_1 and r_2 units perform the function of demagnetizing the drum at the termination of each separate character, thereby eliminating this effect. Demagnetization is accomplished by the reverse discharge of the condenser through the drum via resistance r_2, as explained in the original paper.* In order that this operation shall be performed with precision, it is advisable that the voltage on the circuit of the last valve shall not be less than 80; 100 volts is a good working value.

In addition to its use in a valve circuit the apparatus can be employed in land line or local circuit work, where it would be provided with a second coil for double or reverse-current operation.† The condenser C_2 and resistance r_2 would then be omitted.

This apparatus has been designed entirely on an economy basis so that valves, batteries, etc., have been reduced to a minimum. The recorder (either type), with its associated circuits, can be used for delay-action work, provided an auxiliary reduction gear is incorporated to slow the drum down. The high tension and the valves would require alteration to get the required operating current.

* Loc. cit.
† *Journal I.E.E.*, 1924, vol. 61, p. 908, Fig. 6.

8. Recording Time Signals for Checking Clocks.

The checking of astronomical clocks by wireless signals is sometimes accomplished by causing the incoming signal to operate a relay from the local contacts of which a marking pen is actuated. This pen scribes on a moving paper tape. The clock pendulum closes a local circuit every second, so that another pen also marks on the paper tape. The horizontal distance between the marks of the two pens is a measure of the accuracy of the clock. In this system there are defects due to (1) the lag of the relay, (2) the difference in lag of the relays actuating the two pens.

By using the magnetic drum recorder these lag defects can be reduced to an inappreciable amount and the apparatus brought down to a very simple and compact character. The seconds signals from the local clock are passed through one coil of the recorder and arranged to give a mark of greater duration than that of the wireless time dot. Through the other coil the wireless signal is passed in opposition so that the siphon comes back to the spacing stop momentarily and then goes to the marking stop. The distance on the tape from the beginning of the upward mark to that of the downward one is a measure of the accuracy of the clock. In these two coil circuits the time-lag is different, but the actual lag is so small as to be of no practical importance, the likely errors of measurement on the tape due to thickness of line, etc., far exceeding them. This will be clear when it is remembered that the siphon point moves $\frac{1}{16}$ inch in less than $0 \cdot 002$ sec. and the (time) accuracy required is not more than 5 times this. If, however, the beginning of the up and down lines is taken, the only error is that due to the difference in electrical lag between the circuits of the two coils. It is possible to eliminate this by making the clock operate on the wireless circuit, but this refinement is unnecessary. It is clear that the instrument can also be used for recording time intervals between different types of impulse, e.g. acoustic.

The author acknowledges his indebtedness to the Marconi Co. for permission to publish the data and information embodied in the paper.

THE RUGBY RADIO STATION OF THE BRITISH POST OFFICE.

By E. H. SHAUGHNESSY, O.B.E., Member.

(*Paper received 16th March, 1926; read before the* WIRELESS SECTION *14th April, and before the* SOUTH MIDLAND CENTRE *28th April,* 1926.)

SUMMARY.

This paper gives a general description of the Post Office high-power radio station erected at Hillmorton near Rugby. The introduction sets out the requirements which the design had to meet.

The paper is divided broadly into three Sections :—Power Plant, High-frequency Generating Valve Plant, and Masts and Aerials.

The first Section deals with the selection and type of power plant employed for converting the e.h.t. alternating-current supply to suitable e.h.t. direct-current and l.t. direct-current and l.t. alternating-current supplies for use on the various parts of the installation, and the precautions necessary in dealing with a wireless load of the magnitude involved. The method of providing lighting for the masts for warning aircraft of obstruction is given.

The high-frequency generating-valve plant Section deals with the design of valve generating plant suitable for full-power transmission or subdivision into two transmitters for use with larger and smaller portions of the whole aerial, and gives the methods adopted for maintaining constant frequency, successive amplification and freedom from harmonics. This Section includes :—The e.h.t. direct-current supply ; the general scheme of circuits ; the filament supply ; the excitation unit ; consideration in regard to the size of power unit ; the power unit ; the paralleling of valves in a power unit ; the paralleling of power units ; safety devices and control circuit ; the control table ; types of coupled circuits ; the design of inductances for high power ; relative positions of amplifiers and aerial circuit ; method of keying and shape of signal.

The masts and aerial Section includes :—A brief general description of the 820-ft. masts ; the method of insulating the masts and the stays ; the method of staying the masts ; tensions on the stays, etc. ; the method of applying test load to top of masts ; the aerial system ; aerial insulation ; aerial spreaders ; earth system ; curves of aerial resistance ; voltage on aerial, etc.

The final Section gives the general results obtained to date, and a brief description of the experimental telephony installation.

INTRODUCTION.

When the Government decided upon the provision in England of a wireless station with a world-wide range, the Post Office Engineering Department was entrusted with the task of its erection. The Wireless Telegraphy Commission which was originally appointed under the chairmanship of the late Lord Milner with Dr. W. H. Eccles (Vice-chairman), Mr. E. H. Shaughnessy and Mr. L. B. Turner as members, undertook the general design of the station. The Post Office engineers in consultation with the Wireless Telegraphy Commission carried out considerable preliminary experimental work and prepared detailed drawings and designs for the station equipment as a whole and for most of the plant; they also prepared the detailed specifications to which manufacturers have designed or made the remainder of the plant.

In the preliminary design of the station it was considered that in order to ensure reliable communication when working on a wave-length of about 18 000 m (16·66 kilocycles) a minimum working current of 500 amperes in an efficient aerial supported on 820-ft. masts would be required. To meet this requirement and provide a safe working margin it was decided that the high-frequency generating valve plant should be capable of dealing with an input of 1 000 kW to provide for a possible necessary low working efficiency of 50 per cent. Such an installation would produce an aerial current of about 700 amperes to meet bad atmospheric conditions.

Originally it was considered that sixteen 820-ft. masts would be required to support a suitable aerial, but to avoid any unnecessary expenditure it was decided to erect in the first instance an aerial having a designed capacity of 0·045 μF on 12 insulated 820-ft. masts and to carry out tests to ascertain the limitations imposed on the aerial power obtainable by such factors as corona, insulation, etc., and to obtain data as regards the range of the station using this maximum power.

In order to keep this description of the Rugby radio station within reasonable limits it is proposed to describe the power plant and the external plant briefly and the radio-telegraph plant in detail.

SITE.

Owing to the large area required, considerable difficulty was experienced in obtaining a site, but ultimately an area of 900 acres (about 1½ miles long by 1 mile wide) bounded on the east side by Watling-street and on the west side by the Oxford canal was obtained at Hillmorton about 4 miles south-east of Rugby. The ground is level and not surrounded by hilly or wooded country, although a fox covert on the site had to be demolished, as it was under the proposed aerial. A water supply is available from a stream running through the site; the nearby railways and the Oxford canal afford transport facilities. The station buildings are erected about the middle of the site (see Fig. 1).

POWER PLANT.

The question of the power supply for the station was one which was very carefully considered and, after a close examination of conditions on the basis of comparative costs and reliability, it was decided to accept a bulk supply from the Leicestershire and Warwickshire Electric Power Co., who are the authorized suppliers in the area.

The company has generating stations at Warwick and

Hinckley, the Rugby area being served by duplicate mains from Warwick, whilst arrangements for linking with Hinckley are in contemplation. The incoming supply is three-phase, 50-cycle alternating current, having an earthed neutral and 12 000 volts between phases.

Duplicate underground cables are provided between the radio station and the company's substation at Rugby, where automatic regulators are installed.

The two feeder cables terminate at the radio station in a separate selector switch cubicle which permits of either or both cables being connected to the e.h.t. alternating-current switchboard.

The radio-station power house consists primarily of a machine room 185 ft. by 47 ft. spanned by an 11-ton overhead travelling crane. The general layout is shown in Fig. 2. One end of the room is partitioned off for work shop and stores to which the crane has access and which can be readily utilized for extensions if this becomes necessary. Parallel with the main room is an annex, the lower portion of which contains a battery room and six trans-

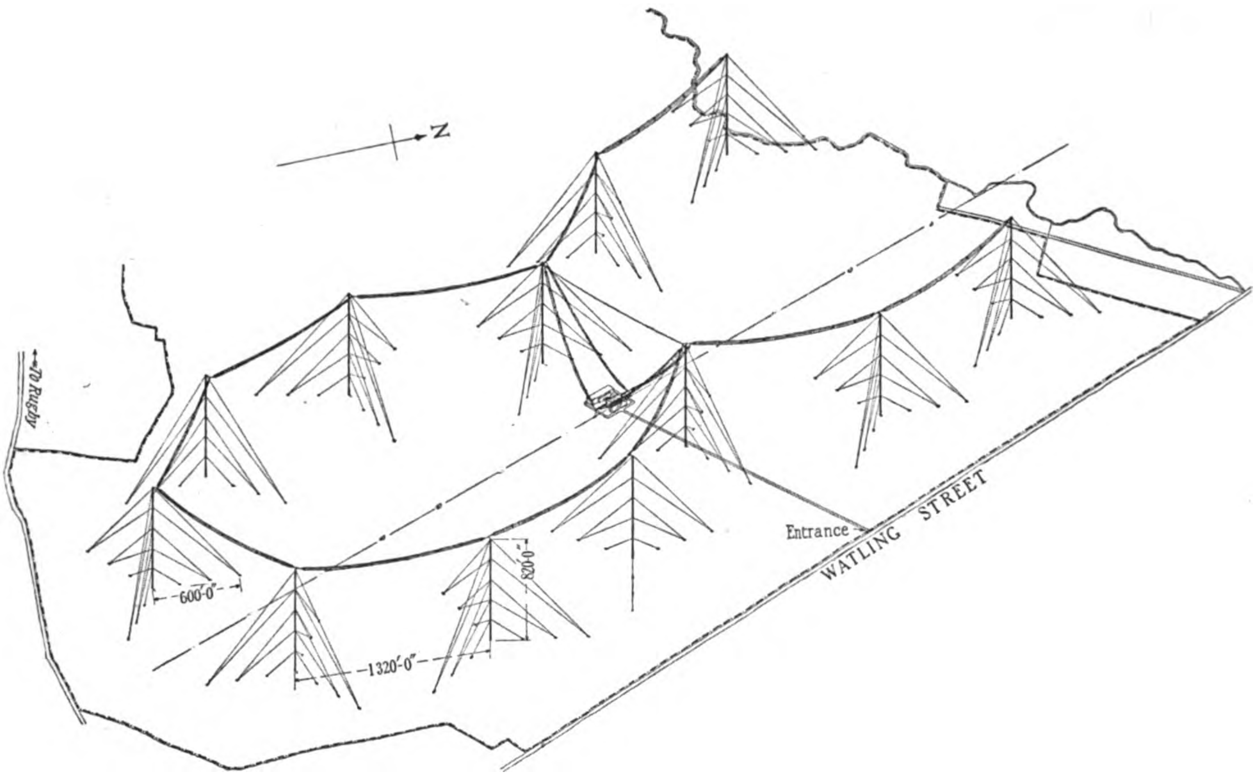

FIG. 1.—Isometric view of station.

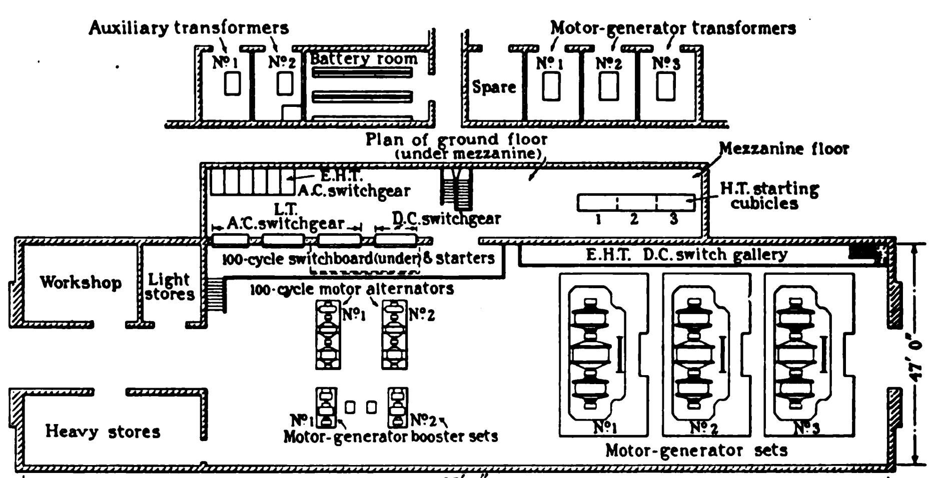

FIG. 2.—Plan of power house (scale $\frac{1}{40}$ in. = 1 foot).

former rooms. A separate room is provided for each power transformer and these rooms can only be entered from outside the building. They are closed by steel doors furnished with ventilating louvres. The upper floor of the annex is a switch gallery open to the machine room. This gallery contains the high- and low-tension a.c. switchboards, high-tension a.c. starting cubicles for the main generators and low-tension d.c. switchboard.

In the machine room are the main motor-generator sets for providing high-tension direct current to the valves, two frequency-converter sets used for heating valve filaments, together with motor starting cubicles and alternator control panels, and lastly two motor-generator and booster sets for battery charging and low-tension d.c. supply.

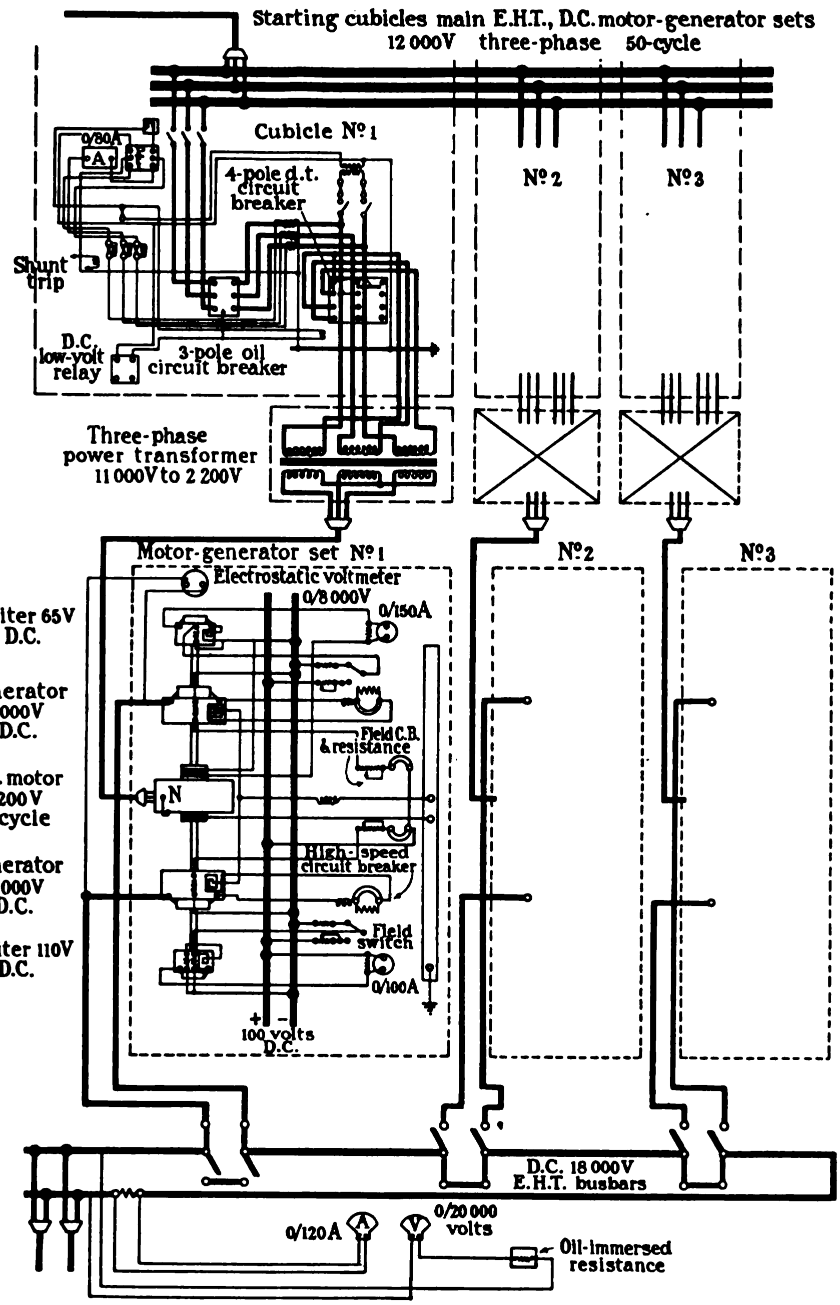

FIG. 3.—Wiring diagram of motor-generator sets.

All power used, other than that required for the main motor-generators, is supplied by two auxiliary step-down (12 000/416 volt) transformers of 450 kVA output through the main low-tension a.c. switchboard. For reasons explained later it was found more convenient to supply

each main motor-generator set through a separate transformer.

The larger motors (i.e. over 100 kW) installed are synchronous machines capable of operating on 0·9 leading power factor, and as a result the station can be operated on unity power factor.

The e.h.t. a.c. switchboard is a 6-panel board consisting of 5 truck cubicles and a metering cubicle. The first truck contains an oil switch controlling the supply to busbars and also contains the company's meters with their respective instrument transformers. The next panel consists of a cubicle containing the Department's check meters and potential transformer.

The four remaining panels are feeder truck cubicles, two being connected to the auxiliary 450-kVA transformers situated immediately below the switchboard, whilst the third, of 2 000 kW capacity, controls the supply to the main motor-generator sets. The fourth truck is at present spare and interchangeable with the remaining three feeder trucks. The low-tension a.c. 416-volt switchboard is of the normal slate pattern containing 16 panels, and controls all auxiliary power inside the station and the outside feeders to mast winches, pumps, etc. These switchboards, together with a number of other switchboards and cabling, were supplied and erected by the General Electric Co., Ltd.

The requirements of the valve transmitter set called for a supply of d.c. power of from 1 000 to 1 500 kW at a potential of from 10 000 to 18 000 volts, with the negative side at earth potential, the higher voltage being provided to cope with probable developments in transmitting valves in the near future.

Owing to the possible failure of valves it was essential that whatever type of plant was installed it would have to be capable of standing a dead short-circuit with impunity. Other special requirements were ability to operate under rapidly fluctuating loads, low self-inductance, and absence of voltage ripple.

The relative merits and suitability of machines, mercury-arc rectifiers and thermionic valve rectifiers for this duty were considered. Tenders were invited for the various types and it was finally decided to install motor-generator sets (see also Report of Wireless Telegraphy Commission, Command Paper 1572–1922).

The machines were manufactured by the British Thomson-Houston Co., Ltd., of Rugby and are an interesting development from machines designed for high-tension d.c. traction work. The Rugby generators, owing to the higher voltage and their operation in series, possess several new features, some particulars of which have already appeared in the technical Press and will only be briefly referred to here. Fig. 3 shows a wiring diagram of these sets. Three sets are provided, each having an output of 500 kW at 6 000 volts d.c., and space is provided for the accommodation of a fourth set. Each set consists of a three-phase self-starting synchronous motor of 640 kVA wound for 2 200 volts between phases, rigidly coupled to two d.c. generators connected in series, and two exciters, one of which is the main exciter and the other the motor field exciter; the main exciter provides field current for both d.c. generators and for the field of the motor exciter.

Each d.c. generator is a bipolar machine having an output of 250 kW at 3 000 volts and provided with interpoles and compensating winding. The magnet frames of cast steel are split diametrically and in order to avoid awkward joints in the pole-face windings the break has been arranged through the centre of the main poles which consist of twin poles, each half carrying its own spool. Another unique feature of the magnetic circuit is a band of laminations incorporated in the yoke to provide an undamped path for the commutating flux under rapidly varying loads. The commutator is of the same diameter as the armature, and all metallic parts in the vicinity of the commutator which are connected to the frame are protected by insulating shields. A series of fan blades mounted between the armature and commutator provide a blast of air across the commutator. The brush gear is completely encased in bronze boxes, the connections to which produce magnetic fields directed to blow out from the machine any arc which may be formed at the brushes.

The bearings are each provided with a thermal relay which, in the event of overheating, rings a bell on the control panel and lights an indicating lamp on the hot bearing.

In order to avoid the use of insulated couplings between motor and generators, each set is supplied with power through a separate transformer. These transformers, manufactured by Messrs. Johnson and Phillips, are wound for 12 000 volts on the primary side and 2 200 volts on the secondary side. The insulation of the secondary winding from the primary winding and core bunched was designed for and subjected to a flash test of 50 000 volts. The secondary side is connected directly to the motor terminals by means of a 3-core paper-insulated cable, and all a.c. switchgear is on the primary side of the transformer.

The d.c. controls of each set are mounted on an auxiliary baseplate which carries generator field rheostats and shunt field rheostats for the main exciter and motor exciter.

The main baseplate of each set and the auxiliary baseplate are insulated from earth by being mounted on groups of porcelain insulators. The neutral point of the motor stator is connected to the baseplate. The mid-point between the d.c. generators is also connected to the base-plate through a leakage relay. In this way the potential of any portion of the set relative to the frames is limited to 3 000 volts d.c.

When working in series each set has a baseplate potential corresponding to its position in the circuit; thus the first baseplate will be at 3 000 volts, the second at 9 000 volts and the third at 15 000 volts above earth in each case.

The wiring diagram of the control panels on the auxiliary baseplate is shown in Fig. 4.

Each main baseplate carries two high-speed circuit breakers each connected in series with a generator armature. The high-speed circuit breaker is set for instantaneous tripping on about 5 times full-load current; it inserts a blocking resistance in circuit and at the same time, by means of auxiliary contacts, trips the generator field contactor. The action of the circuit breaker is extremely rapid, the contacts being fully opened within 0·02 sec., whilst in order to suppress the

generator fields as rapidly as possible the field contactors open the circuit without inserting discharge resistances. Each set is completely surrounded by an earthed metallic screen, and the foundations contain a metallic network which is connected to the earthed screens. All controls are operated by means of insulated spindles from a position outside the screens. The e.h.t. d.c. terminals of each set are connected to a 2-position selector switch mounted on a gallery carrying the busbars. In one position the switch connects the machine in series with the busbars, whilst in the other position the machine is isolated and the gap in the busbars bridged. The screened enclosures and busbar gallery are protected by gates having double electrical interlocks. In addition, it is impossible to enter the machine enclosures without first earthing the baseplate, thus preventing any possi-

delta oil switches, overload and low-voltage trips, ammeter and power-factor meter with current and potential transformers. Each cubicle is located on the switch gallery immediately over its associated transformer, to which it is connected by bare conductors passing through porcelain bushings in the floor. In operation the main oil switch connects one end of the three primary windings of the transformer to the line. The second oil switch is of the 4-pole double-throw type with double escutcheon. On closing the starting-throw the inner ends of the primary windings are connected together, the transformer thus being star-connected to the line and delivering 1 270 volts between phases to the motor. The operation of a sliding interlock bar trips the starting-throw and frees the running-throw which can then be closed to connect the transformer

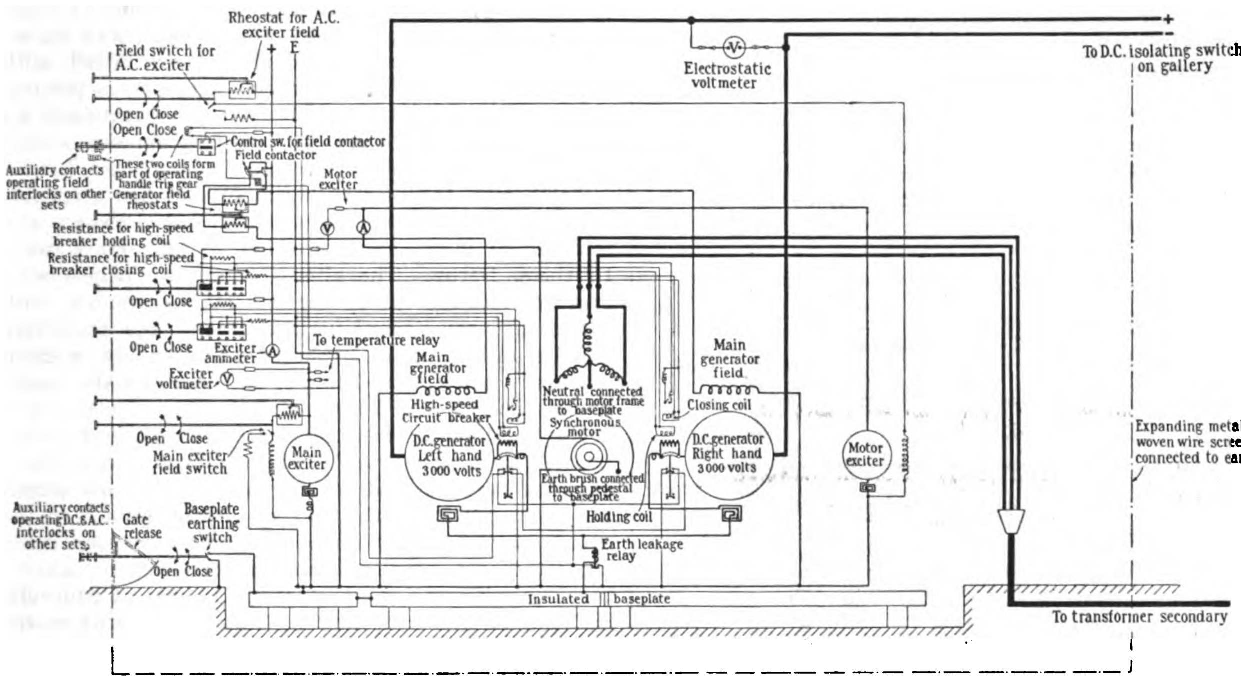

Fig. 4.—Wiring diagram of control panel of 500-kW motor-generator set.

bility of shock from a static charge left on a machine after closing down. A complete system of electrical interlocks external to the machine enclosures is associated with the selector switches, machine controls and a.c. starters. The supply for this interlock system is taken from the 240-volt d.c. battery supply, and no-volt devices are provided to shut down the plant in the event of this supply failing. Any attempt to enter a live enclosure or to operate a selector switch while the busbars are excited will trip the field controls of all running machines. In the event of any generator developing a fault, or in the event of any high-speed circuit breaker opening on overload, means are provided to trip the field controls of all other generators connected to the busbars. As previously mentioned, the motor starting gear for each set is on the 12 000-volt side of the step-down transformer and consists of a steel cubicle containing isolating links, main and star-

primary in delta, giving a normal running voltage of 2 200 volts between phases on the secondary. The switch cubicles were supplied by the British Thomson-Houston Co., Ltd.

In spite of the large dimensions of the machines for their output, necessitated by voltage requirements, the test-results showed an overall efficiency of over 87 per cent.

In addition to the ordinary tests, the machines were subjected to short-circuit tests while fully excited; in the case of one set this test was repeated 20 times, in all cases without flash-over or damage of any kind. A copy of oscillograms taken on a single set by the B.T.H. Co. during the official test is shown in Fig. 5. After installation two short-circuit tests were carried out with all sets in series and fully excited to a total of 18 000 volts d.c. with equally satisfactory results.

The d.c. supply from the busbars is transmitted to the

valve room through duplicate armoured concentric paper-insulated cables, the inner conductor in each case being the high-tension conductor, whilst the outer conductor carries the return current at approximately earth potential. The cables terminate in a steel cubicle

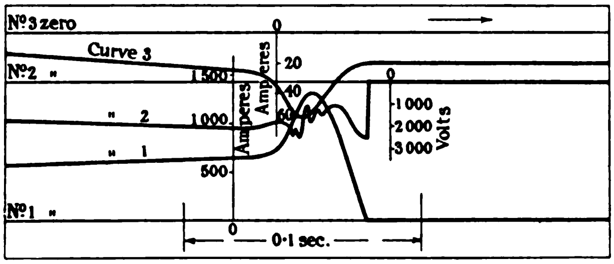

FIG. 5.—Oscillogram of short-circuiting test on 500-kW, 6 000-volt motor-generator set.

Curve 1.—Short-circuit current (1 cm = 756 amps.).
Curve 2.—Voltage across high-speed circuit breaker, commutating pole and compensating windings (1 cm = 3 271·8 volts).
Curve 3.—Shunt field current (1 cm = 48 amps.).

switchboard (Fig. 6) supplied by the General Electric Co., Ltd., consisting of two cubicles each provided with isolator and earthing switches, electrostatic voltmeter, and an electrically operated single-pole 18 000-volt d.c. oil circuit-breaker provided with overload and no-volt

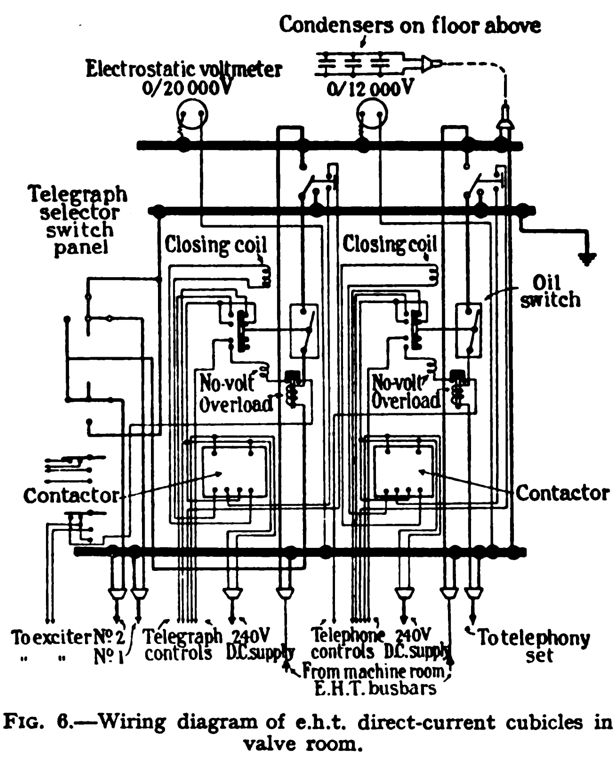

FIG. 6.—Wiring diagram of e.h.t. direct-current cubicles in valve room.

trips. The no-volt trip coil on this switch forms part of a low-tension d.c. circuit and will be referred to subsequently as the "holding coil." One cable terminates in each cubicle, one cubicle being used to supply the main telegraph transmitter, and the other cubicle serving the experimental telephone transmitter. In addition the telegraph cubicle has a selector switch interlocked with the oil switch which connects the e.h.t. d.c. supply to one of two short alternative feeders to the telegraph transmitter, the unused feeder being earthed. The oil circuit-breaker is designed to trip rapidly on interruption of the "holding coil" circuit which is energized from the 240-volt d.c. supply, and during tests the contacts opened 0·18 sec. after interruption of the "holding coil" circuit.

The use of oil circuit-breakers to rupture high-tension d.c. circuits is thought to be a novelty, but tests on short-circuits of 18 000 volts showed that the switch could successfully clear the fault without damage.

The valve filament supply of the station is obtained from two 200-kVA frequency-converter sets each consisting of a 416-volt 50-cycle synchronous motor driving a 200-kVA 354/478-volt 100-cycle three-phase alternator. Each set is provided with a pony motor and exciter. Tirrill regulators are provided on each alternator control panel to limit a.c. voltage fluctuations, and as an additional safeguard the regulators are fitted with excess-voltage cut-outs to provide against the possible failure of the regulator. The voltage maintained by the Tirrill regulators can be varied by remote control from the valve room.

These sets, together with the smaller d.c. generator and other motor-generator sets installed elsewhere and referred to later, were provided by Messrs. Newton Brothers, Derby. The alternator control panels were provided and erected by the General Electric Co., Ltd.

For the operation of various control and protective circuits, and as an emergency lighting supply, a small secondary battery consisting of 120 cells of 200 ampere-hours' capacity has been installed. For charging this battery, 30-kW induction-motor-driven generator and booster sets are provided in duplicate. Automatic switches are provided to short-circuit and disconnect the booster, leaving the battery on the busbars in the event of the motor stopping, the generators being protected by overload and reverse-current circuit breakers. The d.c. busbar voltage is kept at 240 volts and the booster supplies the difference between the battery voltage and this value.

The workshop situated at one end of the power house is provided with a work bench and a number of power-driven machine tools including a 6-in. screw-cutting lathe, 21 in. vertical drilling machine, power hacksaw and shaping machine.

All circuits and machines are provided with protective devices designed to prevent damage from high-frequency currents. On the e.h.t. direct-current generator set, spark-gaps having non-inductive resistances in series are connected across each generator armature. On other machines or feeders straight-filament lamps in cast-iron boxes are shunted across the machine terminals or feeder. In a few cases where the machine current is small a condenser of 2 μF capacity with lamps in series is used.

The switchgear in the valve room consists of the steel cubicles for controlling the e.h.t. direct-current supply and a dead-front board of 20 slate panels carrying all auxiliary supplies for the telegraph transmitter, together with some of the supplies for the telephone sets. A small dead-front slate board of 4 panels supplies all other power required for the experimental telephone set.

The 20-panel board controls the supplies for filaments, grids and anodes of the earlier valve stages and for grid bias of the main valves. The supplies are obtained from duplicate motor-generator sets housed in a small machine room adjoining the valve room.

Other supplies provided by this board are a 240-volt d.c. supply for switch controls and machine excitation, a 50-cycle 416-volt three-phase supply to motors of motor-generator sets and air compressors for keys, a 300-volt d.c. supply for the grid bias of the experimental telephone transmitter, and lastly the 354/478 three-phase 100-cycle supply for heating valve filaments on the telegraph and experimental telephone sets.

Two sets of busbars are provided for the filament supply, one set being associated with each alternator, to which it is connected through a remote-controlled solenoid-operated oil switch. The filament supply to individual valve panels of the telegraph set is taken through a double-throw 3-pole switch on the front of the board and then through a 3-pole contactor mounted behind the board. The double-throw switch enables the valve panel to be connected to either set of busbars, whilst the contactor is in each case remote-controlled from the valve panel where a step-down transformer is situated.

The switchboard and contactors were supplied by the General Electric Co., Ltd.

While on the subject of power supply it may be interesting to mention that a supply of current was required for providing aircraft obstruction lights on certain masts. As the masts are highly insulated from earth it was impracticable to take supply directly from the mains. The difficulty was overcome by mounting a 2-kW 240-volt d.c. dynamo on the mast and driving it by means of a suitable 50-cycle squirrel-cage motor on the ground through the medium of a rubber motor-cycle belt. The motor, which is a totally enclosed weatherproof machine, is provided with automatic starter actuated by a Venner time switch so that the lights are automatically switched on at sunset each evening and switched out at dawn.

High-Frequency Generating Valve Plant.

The high-frequency generating plant was designed to utilize thermionic valves and to be capable of dealing, if necessary, with an output to the aerial of 500 kW continuously under commercial conditions. For the purpose of preliminary calculations the wave-length was taken as 18 000 m, the capacity of the aerial as $0 \cdot 045\ \mu F$, and the total aerial circuit resistance as 1 ohm.

The aerial was designed so that it could be used as one large aerial or be readily divided at the station building into two unequal parts to provide for simultaneous telegraph transmissions on two aerials, and for this purpose two separate down-leads were provided.

The high-frequency generating plant had therefore to be so designed that it could be readily used for such simultaneous transmissions when necessary. However, after the plans had been prepared it was decided to carry out experiments in transatlantic telephony from Rugby in association with the American Telephone and Telegraph Co., and the smaller part of the aerial has been reserved for this purpose for the present and so diverted from its intended function of forming part of a large aerial for the full telegraphic power of the station, or of being used for a second radio-telegraphic channel.

In consequence, the aerial immediately available for the telegraph transmitter is the larger part erected on 8 masts which has a capacity of $0 \cdot 033\ \mu F$. The resistance, as measured after erection, of this aerial at various frequencies in the region of the required transmitting frequency with the masts insulated, is given by curve A of Fig. 7. Curve B of the same figure gives the total resistance of aerial and aerial tuning inductance.

It is essential with the ever-increasing number of transmitting stations that special efforts should be made to maintain constant the frequency of a radio transmitting station and thus reduce the possible interference to a minimum by permitting the use of highly selective receivers.

It was therefore decided to investigate and, if possible, develop the use of the valve-maintained tuning-fork of Eccles and Jordan as a primary source of con-

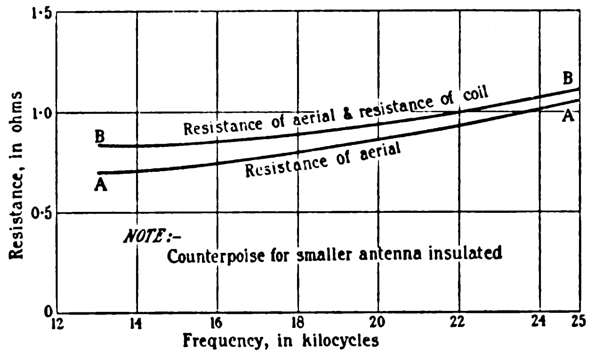

Fig. 7.—Curves of aerial resistance, etc.

Curve AA.—Resistance of telegraphy antenna ($0 \cdot 033\ \mu F$).
Curve BB.—Total resistance of aerial circuit with $0 \cdot 033\ \mu F$ antenna.

stant oscillations. The Post Office research staff produced a suitable combination which was tried out commercially at the Post Office Northolt valve station and proved successful.* The primary source or master oscillator at Rugby is a valve-maintained tuning-fork having a frequency of about 1 800 cycles per second (this frequency being adjustable within small limits), and the high frequency required for controlling the main set is obtained by selecting the 9th harmonic of the tuning-fork frequency.

The frequency produced by this means is remarkably constant, the frequency variation with temperature of the tuning-fork being about 1 cycle in 10 000 per degree C. A small adjustable electric heater is provided to enable the temperature of the box containing the tuning-fork to be kept constant.

The "tuning-fork" stages of amplification may be briefly described as follows. The output from the valve-maintained tuning-fork is of the order of micro-watts, and this is amplified once at low frequency. The 9th harmonic is then selected, filtered and amplified three times with low-voltage valves, giving a final output of 100 watts from the last of these three stages. The tuning fork and all the above stages of amplification

* A. G. Lee: *Electrician*, 1925, vol. 94, p. 510.

are contained in two copper boxes mounted one above the other, the various stages being carefully screened from each other by copper partitions, and this complete unit is termed the "tuning-fork unit." The connections of this unit are shown in Fig. 8.

The output from the tuning-fork unit is amplified three times before it is delivered to the aerial circuit, the various stages being designed to deal with input building and shows the layout of the high-frequency generating plant, etc. The excitation units are seen in duplicate on the right, and the five power units on the left.

The switchboard immediately behind the control table is the 20-panel switchboard, referred to previously, which is associated with the filament supply to the amplifiers and the machines in the auxiliary machine room immediately behind this switchboard which supply

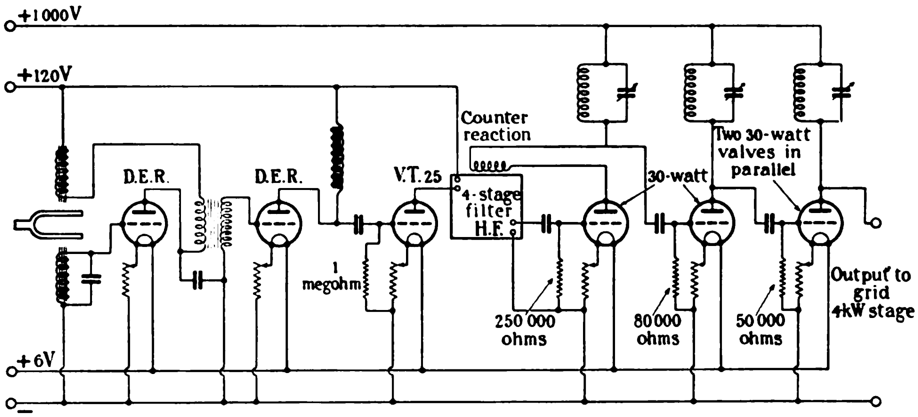

FIG. 8.—Diagram of tuning-fork unit.

powers of the order of 4 kW, 50 kW, and 1 000 kW respectively, and giving output powers of 2 kW, 30 kW and 540 kW respectively. These are referred to as the 4-kW stage, the 50-kW stage and the "power units" respectively. The combination of the 4-kW stage and its associated 50-kW stage forms an "excitation unit." Excitation units and tuning-fork units are provided in duplicate so as to reduce to a minimum the possibility

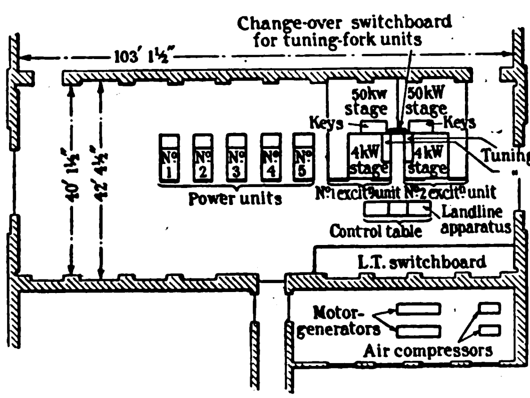

FIG. 9.—Plan of transmitting building.

of delay due to faults, and the arrangement is such that either tuning-fork unit can be used with either excitation unit and either excitation unit can be used to drive the final stage of amplification, which consists of a number of power units.

All the stages and units are contained in high-tension enclosures. The arrangement has been so planned that all meters can be read conveniently, and so that such tuning adjustments as are necessary while the power is on can be made from outside the high-tension enclosures.

Fig. 9 is a plan of the ground floor of the transmitting

the power for the earlier stages of amplification in the tuning-fork unit, the grid bias voltages, compressed-air pump motors, etc.

The main high-tension d.c. switch is remote-controlled from the control table.

The final stage of amplification (i.e. the power units) is not provided in complete duplicate as in the earlier stages. The power-station practice of having a number of units capable of being worked in parallel on common busbars has been adopted. The principal advantages of such a system are :—

(1) It permits an easy flexibility as regards power required for a particular transmission at a particular time of the day, which may be very important from the point of view of not having more valves in use than required and so reducing the consumption of power and also valve replacement costs, which are likely to be a large item in the maintenance costs of the station.

(2) It provides a simple method of repairing a faulty unit or of replacing worn-out or faulty valves while the station is in action.

(3) The installation can be easily adapted to provide either two simultaneous transmission on separate aerials, or a single transmission at larger power on a combined aerial.

(4) It gives facilities for testing different types of valves.

HIGH-TENSION D.C. SUPPLY.

The excitation units and the power units are designed to utilize the same voltage high-tension d.c. supply, and a simple arrangement permits this h.t. supply to be switched on to the 4-kW stage, the 50-kW stage and

whichever power units are in use, by the pressing of a single button on the control table, and ensures at the same time that all accessible units are " dead."

(4) The change-over switch of (1) also makes the necessary transfers in the control wiring of (3) as between the excitation units.

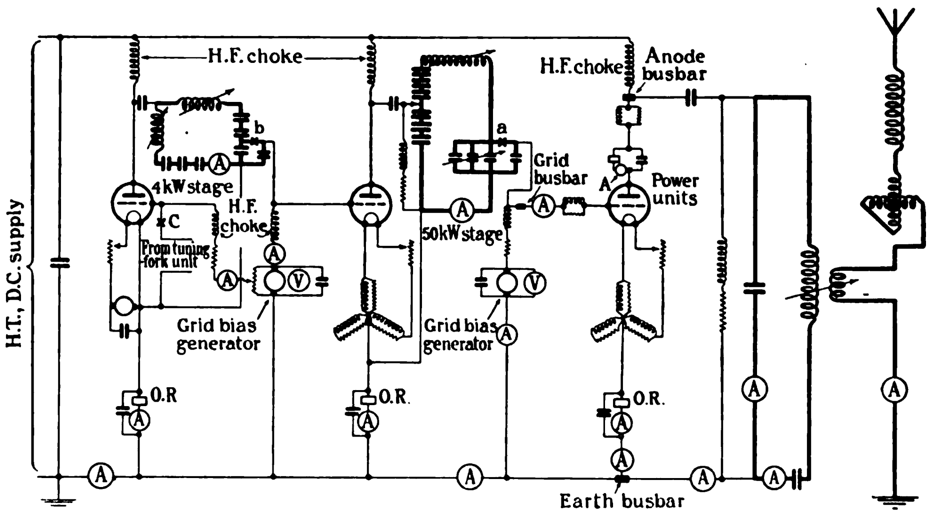

FIG. 10.—Diagram of transmitting circuits.

The general scheme adopted is as follows :—

(1) A change-over switch is provided which connects the h.t. supply to one or other of the excitation units.

(2) The h.t. supply is fed through the excitation unit to the busbar supplying the power units.

(3) All the safety switches and devices form a " series " circuit with the " holding coil " circuit of the high-tension d.c. switch, which is remote-controlled from the control table.

GENERAL SCHEME OF CIRCUITS.

Fig. 10 is a skeleton diagram of the circuit arrangements from the output of the tuning-fork unit to the aerial, showing the circuits between the 4-kW stage and the 50-kW stage, between the 50-kW stage and the power units, and between the power units and the aerial. The tuned high-frequency circuits at the various stages are indicated by the thick lines. A particular characteristic of the circuits is the use of a single tuned circuit between one stage of amplification

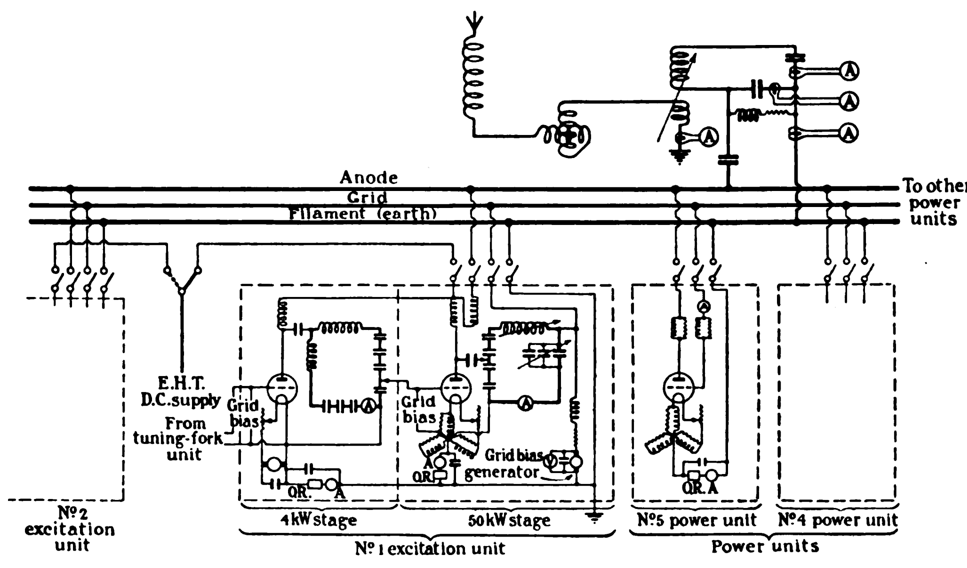

FIG. 11.—Skeleton diagram of arrangement of busbars.

and the next, and the use made of capacitative coupling for giving the necessary voltage variations on both anodes and grids. Some of the advantages of such capacitative couplings are :—

(1) A condenser provides a low-impedance path for the harmonics necessarily generated by a valve transmitter when it is operated as an efficient power amplifier, and thus acts as a desirable harmonic filter.
(2) The actual voltage-swings are easily and accurately calculable both for design and during adjustment.
(3) The power factor of a good condenser being very low, the voltage and current are practically in quadrature.

Fig. 11 is a schematic diagram showing the method of feeding the high-tension d.c. supply through a selected excitation unit to the power units by means of the busbars, and the method of paralleling the power units by means of the same busbars. It will be observed that there are three busbars running the length of the installation for the anode, grid, and filament (earthed) respectively, and that to bring a particular unit into operation in parallel with others it is only necessary to connect it to the busbars by one 3-way switch, and to light the filaments by means of the filament switch for that unit.

In order to simplify this system of paralleling, all apparatus proper to the complete amplifier formed by the power units as a whole, such as anode choke, grid leak, etc., are provided in duplicate and placed inside the respective excitation units.

Filament Supply.

The filament supply for the power units and the 50-kW stage is at 416 volts, three-phase, 100 cycles, transformed down to the required voltage for the filaments (about 20 volts) by transformers in the units themselves. As previously stated, a Tirrill regulator is provided for the 416-volt supply to keep the voltage on the valve filaments constant; this is very important from the point of view of conserving the life of the valves. The filament load of each power unit and each 50-kW stage is balanced between the three phases so as to reduce the effect of any periodic change of emission current due to the use of alternating current for filament heating.

The filament supply for the 4-kW stage is at 15–20 volts d.c. supplied by one of the generators in the auxiliary machine room.

The Excitation Unit.

The 4-kW stage utilizes glass valves of the so-called 600-watt type—i.e. capable of a dissipation of 600 watts—and the panel can be equipped with 1, 2 or 3 of such valves. The valves are mounted on insulators fitted on the back of the slate panel on which the instruments for this stage are mounted.

The 50-kW stage utilizes three water-cooled valves similar to those in the power units, and the manner of mounting, etc., is similar to that of the power units.

The coils forming the inductances of the high-frequency circuits of both stages are constructed of cable of insulated and stranded wires, the cable being wound on a framework of American whitewood in a manner similar to that adopted for the large tuning inductances described later. The cable of the 4-kW stage inductance is 243/36 S.W.G. and that of the 50-kW stage is 729/36 S.W.G. The condensers of these high-frequency circuits are mica condensers in oil.

The safety devices, relays, etc., are similar to those used in connection with the power units.

Associated with each excitation unit is an auxiliary machine unit consisting of one motor driving four generators. These generators have the following ratings and are utilized for the following purposes :—

(1) 500–1 500 volts, ⅓ amp. Anode supply for various amplification stages of tuning-fork unit.
(2) 15–20 volts, 60 amps. Filament supply for 4-kW stage, and also for tuning-fork unit by means of potentiometer.
(3) 40–600 volts, 12 amps. Grid-bias voltage for power units.
(4) 200–600 volts, 1·5 amps. Grid-bias voltage for 50-kW stage and also for 4-kW stage by means of potentiometer.

The motor driving this unit has a remote-controlled starter so that all the various auxiliary powers required are obtained by the pressing of one button at the control table.

With such a chain of amplifiers as that forming this installation one probable difficulty to be combated is the self-oscillation of the system in whole or part due to retroaction from the later to the earlier stages, but this tendency to self-oscillation can be reduced by very careful screening between the various stages. The tuning-fork unit is made up in the form of two copper boxes with copper partitions between the different stages and tight-fitting copper lids to the various compartments. The excitation units and tuning-fork units are placed inside a screened enclosure, the sides and top of which are formed of copper mesh (14 to the inch) mounted on a suitable framework. Internal partitions of similar copper mesh complete the screening between the tuning-fork unit, the 4-kW stage and the 50-kW stage respectively.

Considerations in Regard to the Size of Power Unit.

The number of valves used for a high-power valve transmitter should be reduced to a minimum by using the most powerful valve available as a unit. When the design for Rugby was prepared, the largest power valve commercially available which had been subjected to severe traffic tests was the Western Electric water-cooled valve which is capable of dealing with an input of 20 kW, of giving an output of 10 kW and continuously dissipating 10 kW when operated at a d.c. anode voltage of 10 000 volts—the filament consumption being 41 amperes at 22 volts. This type of valve had been tested to 13 000 volts with an output of 14 kW. The specification stipulated that all valves should be tested at an output of 12 kW with 12 000 volts on the anode. All the valves used in the installation were manufactured by the Western Electric Co. at New Southgate, England.

An efficiency of the order of 95 per cent can be expected from the coupled circuit to the antenna, which means that for an aerial power of 500 kW an output from the valves of about 520–530 kW is required. The determining factors in deciding the size and number of the power units were as follows :—

(1) The number of valves in each unit should be preferably a multiple of 3 in order to permit the balancing of the filaments between the three phases.
(2) The number of units must not be unduly large, in order to avoid complications of wiring and excessive duplication of meters, etc.
(3) The number of units should be sufficient to enable the number of valves in use to be varied in suitable steps (*a*) for the station to work on low power if this proves to be economically desirable, or (*b*) for the utilization of a smaller number of greater power valves as the manufacturing technique of power valves develops.
(4) The number of units should be suitable to provide two transmissions of the order of 300 kW aerial power and still leave a spare unit.

These considerations led to the decision to provide 5 power units, each capable of an output of 180 kW from 18 10-kW output water-cooled valves. With this equipment 3 power units would be required for a 500-kW aerial power transmission, leaving 2 units spare; also two transmissions of over 300 kW aerial power could be undertaken by using 2 power units for each, leaving one unit as a spare in reserve.

The Power Unit.

The power unit consisting of 18 valves is a rectangular enclosure arranged with 9 valves on each side and a front slate panel containing the meters.

The 3 busbars run above the various power units and the excitation units and each power unit can be connected to the busbars by a 3-pole switch. The 3-pole switch for connecting a power unit to these busbars cannot be operated until the Bostwick gates on the sides of the unit have been closed and locked, and the keys locked in the switch itself; the converse holds that the gates of the unit cannot be opened until the keys for opening them have been released by the opening of the switch, which "earths" all parts of the power unit. These interlocking devices render the operation of the power units quite safe.

The front panel of a power unit carries the following :—

(1) Ammeter reading high-frequency feed current from the power unit into the oscillating circuit.
(2) Ammeter reading anode d.c. feed current to power unit from high-tension machines.
(3) Ammeter reading mean d.c. grid current of power unit.
(4) Recording ammeter of filament current, by means of which the actual running time of unit and the life of individual valves can be obtained.
(5) An overload relay for the complete power unit which trips the main high-tension d.c. switch.
(6) An "Electroflo" meter which reads the actual total rate of flow of water through the valve jackets of the unit.
(7) A relay in association with the "Electroflo" meter which operates if the flow of water falls below a certain amount, and trips the main high-tension d.c. switch.

Fig. 12 is a section through a power unit parallel to the front, showing the juxtaposition of the various panels. Slate panels have been used in all cases for mounting the various apparatus and fittings, these slate panels being supported and insulated from the earthed iron framework by suitable porcelain insulators.

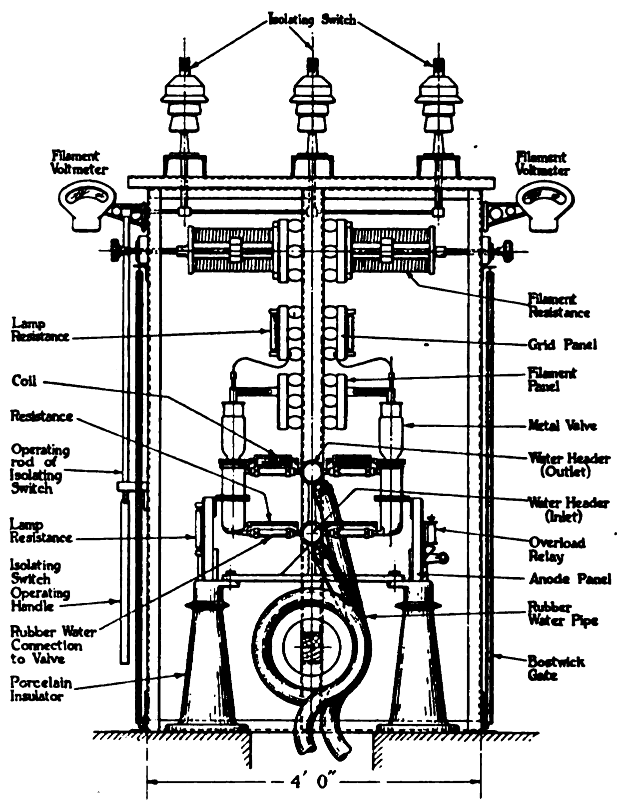

Fig. 12.—Section of power unit.

The two anode panels are supported from the floor by four 18-in. insulators. These insulators also support the copper water pipes between these panels which not only act as headers for the water supply to the anodes but also as the anode busbars for the valves in the panel.

The anode panels carry the valves in their water jackets and the overload relays in the individual anode circuits. In the event of any particular valve taking an excess current due to softness or any other reason, the corresponding relay operates, releasing a hammer normally held up by the armature of the relay, which in turn operates a mechanism that trips the high-tension d.c. switch by breaking the "holding coil" circuit. The arrangement has proved to be very effective, and oscillograms which have been taken show that the h.t. switch is broken in about $\frac{1}{4}$ sec. following an excess of current through the relay.

The water system used for cooling the anodes is a closed system using distilled water which flows by gravity through the valves. The water is pumped from the bottom tank back to the upper supply tank through a "water cooler," where the heat is extracted by an independent circulating-water system.

The distilled water is supplied to the anodes of the power unit through 30 ft. of 2-in. diam. rubber hose wound on a horizontal wooden drum at the bottom of the power units. This rubber hose feeds the 3 in. copper header which passes down through the centre of the unit and which in turn feeds the individual valves on each side through short lengths of rubber tubing to the lower ends of the valve jackets. The outlet water from the upper ends of the valve jackets passes to a similar header which discharges through another length of 2-in. hose similar to that used for the inlet water and wrapped round the same drum. The long length of water in the rubber hose provides the necessary insulation of the anodes from the earthed metal parts of the water cooling system, and the drum carrying this hose is a part of the insulated anode system. The short lengths of rubber tube from the headers to the valves provide the insulation required between valves to permit the insertion of relays, coils, etc., in the individual valve anode circuits. The porcelain floor insulators and the large rubber hose are shown in Fig. 12.

The insulation of the anode system of one power unit under working conditions with water flowing is of the order of 520 000 ohms, giving a leakage current through the water of only 20 mA at 10 000 volts.

Immediately above the anode panels are the filament panels which carry the filament busbars for the unit and the flexible braided leads from these busbars to the separate valve filaments. Above the filament panels are the grid panels, which carry the grid busbar (in the form of a complete loop of copper strip between the panels) and also any "stopper" circuits referred to later.

Above the grid panels are the filament rheostats, one of which is provided for each valve, together with a voltmeter key to enable the actual filament voltage to be read by means of a swinging voltmeter at the end of the panel. This independent variation of the filament voltage in order to obtain the rated value for each valve is very necessary in order to conserve the life of the valves, the life being seriously shortened if the filament is continuously run slightly above its rated voltage.

The Paralleling of Valves in a Unit.

One of the difficulties in designing a large power transmitter using a large number of valves is the tendency of such valves to "self-oscillate," individually or in groups, the inter-electrode capacity of adjoining valves or groups of valves forming the condenser of the oscillating circuit in association with the inductance of the connecting leads, etc. These difficulties are increased with water-cooled valves where the existence of the water jacket increases the intervalve and inter-electrode capacities very considerably. Every such difficulty of this nature must be examined and dealt with separately, and, generally speaking, the oscillations can be suppressed and the system made stable by one or more of the following devices :—

(1) The provision of a small condenser between the grid and filament of each valve, as close to the electrodes as possible, in order to make the grid-filament impedance capacitative.

(2) The use of "stopper" circuits in the individual anode, and/or grid circuits consisting of an inductance in parallel with a resistance high compared with the impedance of the inductance at the transmitted frequency. For undesired oscillations, however, which are of a much higher frequency, the added inductance becomes a large proportion of the inductance of the circuit, and the resistance across it provides sufficient damping for the conditions of self-oscillation of the valves to be unfulfilled (Western Electric Co.).

(3) The insertion of a series resistance in the individual anode or/and grid circuits which act as a damping for self-oscillation but are not of high enough value to cause a large power loss at the transmitted frequency.

The best arrangements for a particular case must be obtained by experiment, and quite a number of combinations of such devices would probably be equally successful. It is generally desirable to allow a factor of safety on such devices by fitting more than the minimum absolutely essential, so as to provide for the contingency of faults which might otherwise permit self-oscillation, with the consequent possible destruction of a number of costly valves.

The arrangements used successfully at Rugby are :—

(1) Two small condensers of 400 $\mu\mu$F each are mounted on each valve between the grid and each end of the filament.

(2) A series non-inductive resistance of 100 ohms between each individual grid and the grid busbar.

(3) The anode feed from the individual valves to the top water header (which acts as the anode busbar) consists of an inductance of 50 μH in parallel with a non-inductive resistance of 60 ohms to the same header and a similar non-inductive resistance to the bottom water header, these two headers being metallically connected at the end of the panel.

Fig. 13 gives the circuit arrangements of a complete power unit.

The Paralleling of Power Units.

The paralleling of the power units themselves also involves consideration as to the method of prevention of inter-oscillation between power units.

At Rugby the combined anode of the power unit is fed to the main anode busbar through a "stopper" circuit consisting of an inductance of 100 μH in parallel with a resistance of Morganite plates of 8·5 ohms. The combined grid of the power unit is fed to the main grid busbar through a "stopper" circuit consisting of an inductance of 50 μH in parallel with a resistance of 300 ohms formed by 6 straight-filament lamps in series. The positions of these in the circuit are shown in Fig. 13.

These "stopper" circuits are fitted at the back of the power unit in the space above the filament transformer and immediately below the 3-pole power unit isolating switch, to two terminals of one side of which they are connected.

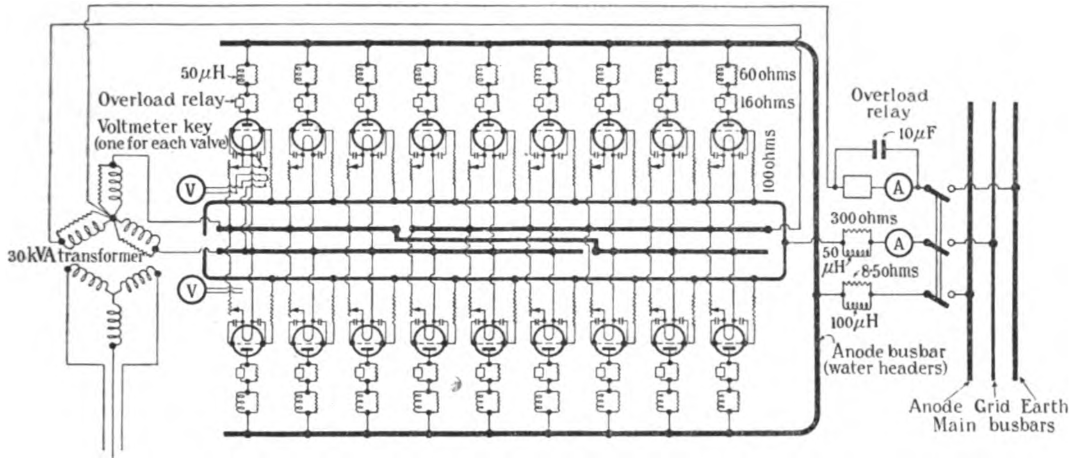

FIG. 13.—Wiring diagram of power unit.

SAFETY DEVICES AND CONTROL CIRCUIT.

The safety devices can be divided into two groups :—

(1) Those for the protection of the personnel.
(2) Those for the protection of plant.

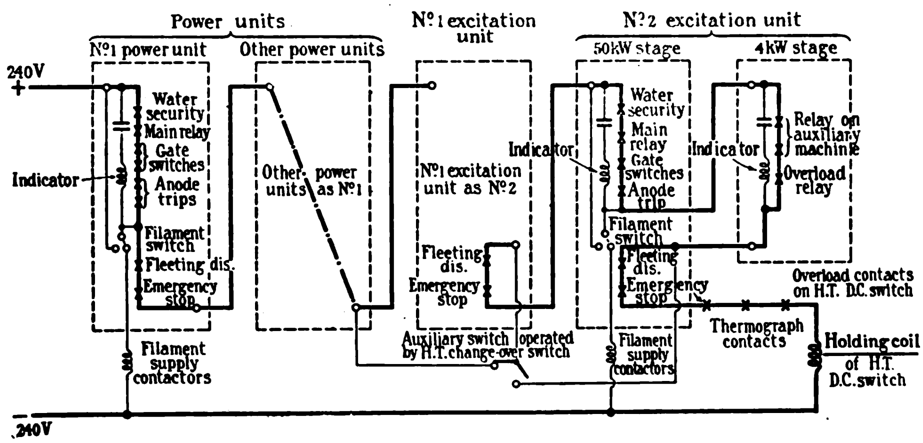

FIG. 14.—Skeleton diagram of control circuit.

For the protection of personnel, the interlocking of the gates of the power units as described previously, and the earthing of the unit when the isolating switch is open, safeguard the station staff from electric shock when working on the power units. A similar arrangement is provided in connection with each excitation unit. The 4-pole isolating switch (see Fig. 11) which connects the high-tension d.c. power to the excitation unit, and the excitation unit to the main busbars is similarly interlocked with the gates of the excitation unit enclosure.

The protection of plant is of special importance when using valves, because, firstly, the closing of the h.t. switch for a very short period under incorrect conditions might result in the destruction of a number of valves, and secondly, there is a possibility of valve failures which amount to a short-circuit of the 10 000-volt d.c. supply. All the safety devices and relays are therefore linked up in one series circuit through the "holding" coil of the high-tension d.c. switch. A disconnection in any one place will then prevent the switch from being closed, and also the breaking of the circuit at any point during transmission due to a fault or an overload will open the high-tension d.c. switch.

Fig. 14 is a skeleton diagram showing the circuit arrangement of this "series" control wiring through the "holding" coil of the high-tension d.c. switch. The main facts to be noticed in connection with it are as follow :—

(1) The series circuit includes one of the two excitation units and whatever power units are in use.

(2) The operation of the hand-operated switch which changes over the h.t. supply from one excitation unit to the other automatically changes over the control wiring and short-circuits that of the excitation unit not in use to permit access for repairs, adjustments, etc.

(3) The placing of the filament switch on a power unit to the " off " position short-circuits the control wiring of that particular unit, and enables work to be done on that unit while the others are in use.

(*d*) Gate switches.

(*e*) A fleeting disconnection during the movement of the power unit isolating switch, to ensure that a unit is not switched on to the busbars while other units are in operation.

(*f*) Emergency push-button.

(2) *On each excitation unit.*

(*a*) Main overload relay for 50-kW stage.

(*b*) Trip operated by individual anode relays of 50-kW stage.

(*c*) Water-flow relay for 50-kW stage.

(*d*) Overload relay for 4-kW stage.

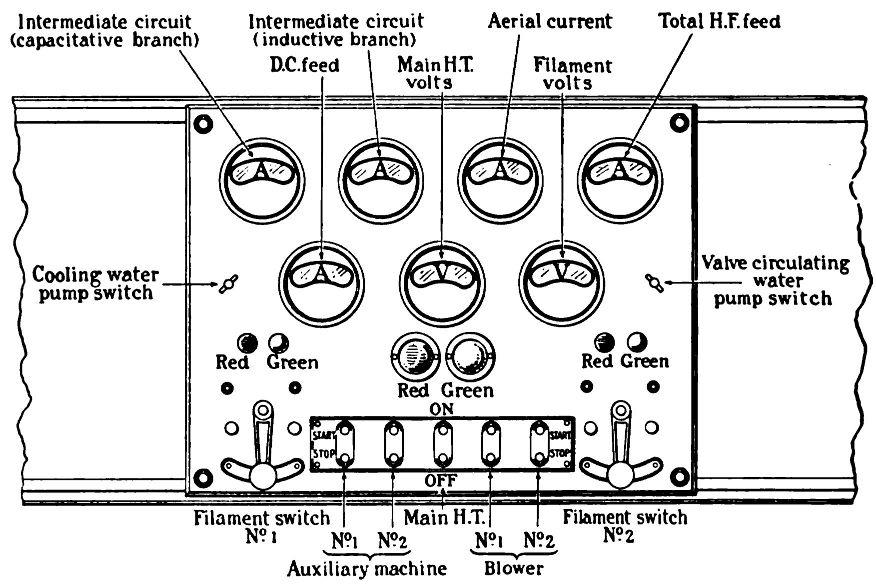

FIG. 15.—Control table.

(4) The placing of the filament switch on a power unit to the " on " position connects the primary of the filament transformer to the filament supply busbars by means of a remote-controlled contactor. The 240-volt supply to operate this contactor is obtained via the control wiring as shown in the diagram, thus ensuring that the filaments cannot be lighted until water flowing through the valve jackets has closed a contact earlier in the circuit.

(5) An indicator is fitted on the front of each power unit panel and placed in series with a condenser across all the contacts of that particular unit. When a break in the control circuit occurs, the charging current from the 240-volt mains into the condenser drops the indicator and gives a visual indication of the particular unit at which the overload or other trouble has occurred.

The operating points of the control circuit may be summarized as follows :—

(1) *On each power unit.*

(*a*) Main overload relay.

(*b*) Trip operated by individual anode relays.

(*c*) Water-flow relay.

(*e*) Gate switches.

(*f*) A fleeting disconnection for the excitation units similar to that of (1*e*) for power units.

(*g*) A polarized relay in association with one of the grid-bias generators to ensure that the auxiliary machine is running and that the bias is of correct polarity.

(*h*) Emergency push-button.

(3) *External to power and excitation units.*

(*a*) A contact in association with a recording thermograph which records the temperature of both the inlet and outlet temperature of the valve-cooling water. This contact is arranged to open if the outlet water exceeds a predetermined temperature.

(*b*) Emergency switch in condenser room.

(*c*) Overload coil of high-tension d.c. switch.

(*d*) Release button on control table.

THE CONTROL TABLE.

The position of the control table in the layout of the transmitting room can be seen from Fig. 9. The slate panel contains all the essential controls and the most important meters of the wireless transmitter. This equipment is shown in Fig. 15 and consists of :—

(1) Press-buttons to start and stop auxiliary machines.
(2) Press-buttons to start and stop air compressor for keys.
(3) Press-buttons to close and open high-tension d.c. switch.
(4) Switch to start distilled-water pump.
(5) Switch to start cooling-water pump.
(6) Switch to close and open main filament supply switch.
(7) Filament supply voltmeter.
(8) High-tension d.c. voltmeter.
(9) High-tension d.c. feed ammeter.
(10) Ammeter reading high-frequency feed current to main oscillating circuit.
(11) Ammeter reading high-frequency current in capacitative arm of primary oscillating circuit.
(12) Ammeter reading high-frequency current in inductive arm.
(13) Aerial ammeter.

The apparatus terminating the land line from the Central Telegraph Office, London, which controls the transmission from the station, is fitted on the right-hand side of the control panel so that the duty engineer can check the signals passing through the transmitter and also speak to the controlling telegraph office as may be necessary.

On the table on the left-hand side of the control panel is fitted an " engine-room telegraph " operated by push-buttons to enable the power requirements to be signalled to the power house. A loud-speaker and wireless recorder are provided for checking the actual signals transmitted from the aerial. In addition there are fitted on this table, two press-buttons controlling a motor-driven variometer in the aerial circuit to compensate for any changes in the aerial constants due to weather, etc.

The duty engineer, therefore, has full control of the entire station in detail from his position at the control table.

The high-frequency and other electrical measuring instruments fitted in the valve transmitting plant were supplied by Messrs. Everett, Edgcumbe.

Type and Electrical Proportions of Coupled Aerial Circuit.

Any large power valve transmitter should be provided with a coupled circuit, since the use of a valve transmitter at reasonably high efficiency necessitates the production of a certain proportion of harmonics, which should be filtered from the aerial. This involves a consideration of the following points :—

(1) Method to be adopted to produce necessary voltage variation on anode (commonly referred to as " type of anode tap ").
(2) Method of coupling to aerial, i.e. inductive or capacitative.
(3) Coefficient of coupling between aerial and primary circuit.
(4) Proportion of inductance to capacity in primary circuit.

The diagrams of Fig. 16 * indicate various circuit arrangements which are referred to as Types A, B, C, D and E respectively.

For an " anode tap " the use of a capacity rather than inductance brings with it a reduction of the harmonics in the aerial in the ratio of $1/m^2$ for the mth harmonic ; that is, types B and D are m^2 times better than types A and C respectively. For preliminary tuning, the use of capacity rather than inductance brings with it the disadvantage of having to be tapped in relatively big steps instead of being continuously variable

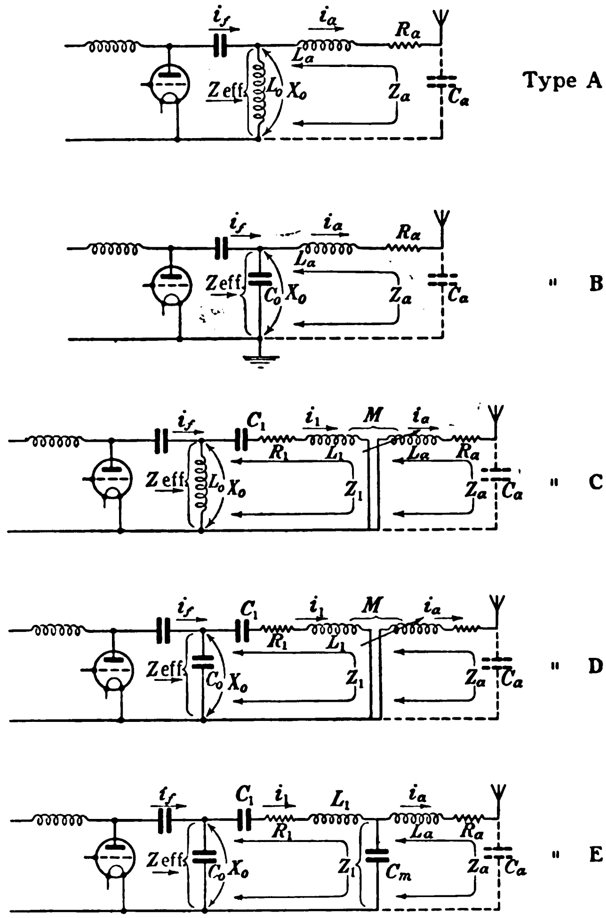

Fig. 16.—Types of output circuits.

as with an inductance ; but, within these steps, variations of coupling between the primary circuit and the antenna circuit will produce equivalent changes in the adjustment of the complete circuit.

Similar arguments apply to the method of coupling the primary circuit to the antenna circuit; that is, as regards the undesirable emission of harmonics, type E circuit is m^2 times better than type D, and therefore m^4 times better than type C. The ideal circuit, therefore, from the point of view of harmonic emissions is that shown as type E with capacitative coupling to both anode and aerial.

In practice, however, when designing a circuit for an

* The author is indebted to Mr. R. V. Hansford and Mr. Faulkner for these diagrams.

aerial not yet erected of which the resistance and capacity are not known accurately, it would be expensive to provide a range of condenser values for both anode and aerial couplings which would cover both all the large and small adjustments required during the experimental period of tuning up the plant. If, however, a type D circuit is used with a condenser having a relatively coarse adjustment for the anode coupling and a continuously variable inductive coupling for the aerial, all necessary adjustments for the preliminary testing can be made with facility; then when the constants of the aerial circuit are known and the preliminary tuning has been completed, if necessary the change from type D to type E can readily be made. It has, however, been found unnecessary to depart from the type D circuit installed.

As regards the emission of harmonics, the improvement obtained by using a coupled circuit of type D instead of a plain aerial circuit is dependent, among other factors, upon the product of the decrements of the primary and aerial circuits. When a low-decrement aerial tuning inductance is provided, the decrement of the aerial circuit at a given frequency is practically fixed, being mainly dependent upon the external part of the circuit.

It is therefore important that the decrement of the primary circuit be made low, and this involves the provision of the most efficient inductance coil and condensers having very low loss. The cost of the primary circuit is roughly proportional to the kVA with which it has to deal, except at the higher voltages where the cost increases rather more rapidly than the kVA.

The efficiency of the coupled circuit and the improvement as regards harmonic emission obtained by using the coupled circuit are both independent of the ratio of inductance to capacity in the primary circuit. Under these circumstances the actual value of the inductance was chosen from a consideration of the following:—

(1) The cost of the coil decreases slightly as its inductance is decreased.

(2) Above a certain working voltage the cost of the condenser increases at a more rapid rate than its capacity.

(3) The cost and difficulty of insulating leads are increased when high working voltages are increased.

This led to the decision to have a primary circuit inductance of the low value of 500 μH. The values of the condensers making up the primary oscillating circuit are given in Fig. 17. The condensers used are mica condensers immersed in oil, made by Messrs. Dubilier to meet the Post Office specification. These have a power factor of 0·00025 at the working frequency. The power factor was tested by an 8-hours' run on each unit on full load and voltage at the maker's works. In addition to the power factor tests each unit of the condenser banks (Fig. 17) was tested at the following voltages:—

Bank A—68 000 volts (R.M.S.) at 50 cycles.
Bank B—25 000 volts (R.M.S.) at 50 cycles.
Bank C—35 000 volts (R.M.S.) at 50 cycles.

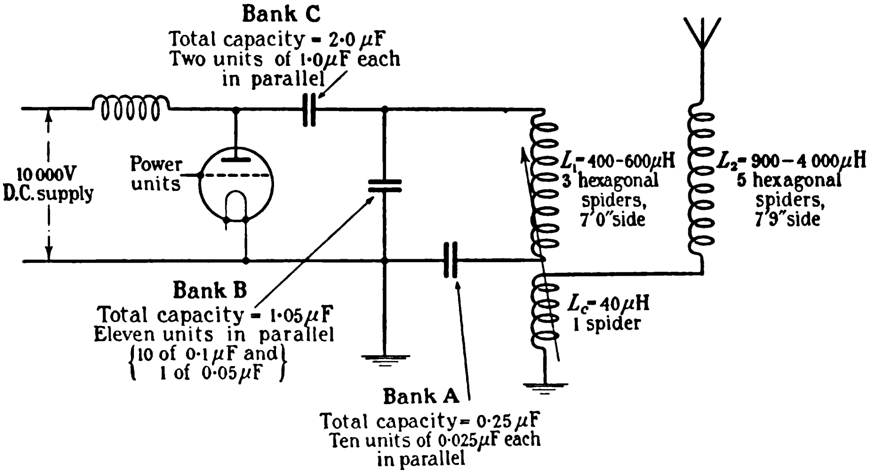

FIG. 17.—Coupled aerial circuit.

The primary circuit is designed to carry a current of 630 amperes, and at this current the value of the R.M.S. voltage applied to the condenser would be 33 000 volts (peak value 46 500 volts) and the kVA 20 800. Actually at present the value of the working primary current is about 300 amperes.

At Leafield the condensers, consisting of aluminium plates immersed in oil and made and erected by the Post Office engineers, have been working for about 2 years with a current of 260 amperes and a voltage of 68 000 (R.M.S.), dealing with 18 000 kVA. The Dubilier type of condenser is much less bulky than the Leafield type and its adoption enabled space to be saved in the Rugby building.

THE DESIGN OF INDUCTANCES FOR HIGH POWERS.

It is essential in a high-power transmitting station that the losses in the primary-circuit and aerial-circuit

inductances should be reduced to a minimum. The losses which add together to form the equivalent resistance of the coil may be divided into the following three groups :—

(1) Losses in the conductor itself.
(2) Losses in surroundings.
(3) Losses in the framework necessary to support the conductor forming the inductance.

The losses in the conductor itself (group 1) have been discussed mathematically in detail by Mr. Butterworth,* and although Mr. Butterworth does not deal with the case of a large coil with widely spaced turns in a deep winding space, the formulæ he has given can be used without serious error *to compare* the efficiency of various designs of coils, etc. At the time the designs were being prepared the practical manufacturing limit as regards number of strands in a cable was 6 561 (= 3^8) and for this number of strands, so far as conductor losses only were concerned, calculations indicated that the diameter of the coil should be as great as the limitations of the space permitted and the diameter of the wire used should be very small and of the order of 0·007 in. It was therefore decided to use a cable of 6 561 strands of No. 36 S.W.G. wire for both the primary and aerial inductances, each strand being insulated by enamel and one covering of cotton or silk. The cables were made to the Post Office specification by Messrs. Henleys Telegraph Works Co., Ltd., and Messrs. Connollys, Ltd. The maximum current-carrying capacity of this cable when wound into an inductance is probably of the order of 1 000 amperes.

With an efficiently designed coil of large dimensions for big powers, the losses in the surroundings and in the inductance framework must necessarily be of the same order as the conductor losses. The losses in the surroundings can only be reduced by having adequate clearances between the inductance and the floors and walls, and by avoiding as far as possible for the construction of the building the use of materials which are likely to absorb energy from the inductances.

A considerable amount of experimental work † has been carried out in the Post Office Engineering Department to ascertain a suitable insulating material for use in the construction of radio transmitting inductances, and it was found that American whitewood was very much better as regards dielectric losses than any other material or any other wood. The method adopted by the Post Office for the construction of transmitting inductances is to mount a cable formed of insulated and stranded wires on a framework of American whitewood. The cable is wound in slots on movable wooden spiders which are supported by rollers on a wooden framework, so that changes of inductance can be obtained by the relative movement of the spiders without the awkward mechanical construction of "tapping points" and the disadvantages of "overhanging" end-turns. The maximum width of the largest inductance coil is 14 ft. 6 in. The particulars and general dimensions of the aerial and primary circuit inductances are as follow :

* *Philosophical Transactions of the Royal Society*, A, 1921, vol. 222, p. 57.
† E. H. Shaughnessy : Chairman's Address to the Wireless Section, *Journal I.E.E.*, 1925, vol. 63, p. 60.

Aerial coil.—This consists of 5 spiders each of 8 turns wound in the form of a hexagon with 7 ft. 9 in. external side (5 ft. 9 in. mean side). Distance between individual turns 6 in. Inductance continuously variable between 900 and 4 000 μH.

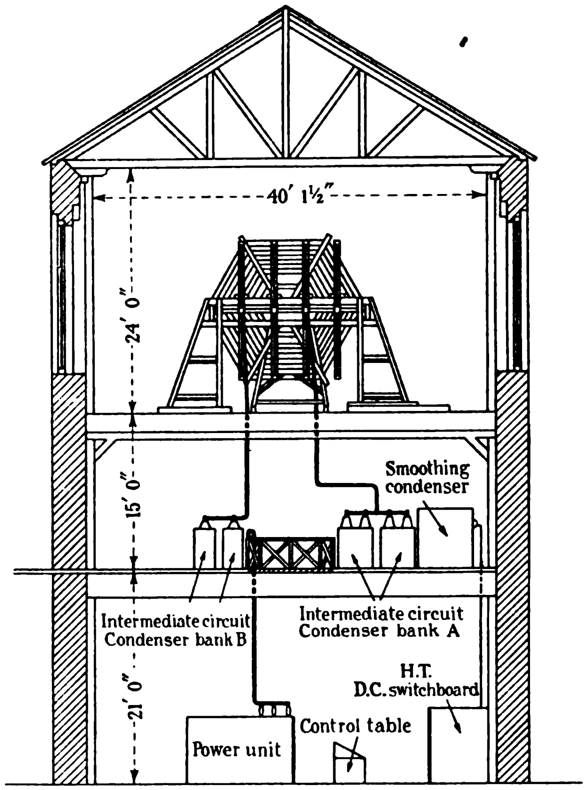

FIG. 18.—Section of transmitting building.

Primary circuit coil.—This consists of 3 spiders each of 4 turns wound in the form of a hexagon with 7 ft. external side (6 ft. 2 in. mean side). Distance between turns 6 in. Inductance continuously variable from 400 to 600 μH.

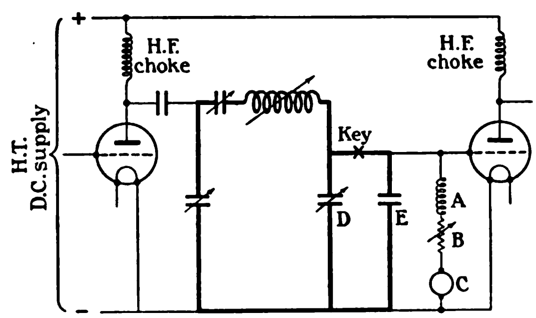

FIG. 19.—Skeleton diagram of inter-stage circuit.

Coupling coil.—One spider wound with 2 turns 6 ft. 5 in. external side. This coil is mounted on the same framework as the intermediate circuit coil and is coupled thereto. Inductance 40 μH.

One outside spider can be moved by a screw in order to get a fine adjustment of tuning. The method of

making a joint in the stranded wire between the spiders is to splay out the strands on a number of insulated flat copper plates and semi-conical copper fittings so as to ensure proper circulation of current through all the strands and to keep a cool joint.

It was estimated at the time of the design, from previous comparisons between actual and calculated decrements of smaller coils, that the decrement of the complete primary circuit would be about 0·003 to 0·005 and that of the aerial tuning inductance would be about 0·002. The actual measured resistance at 16 000 cycles of the entire primary circuit as erected was 0·088 ohm, giving a decrement of 0·0053. The measured resistance of the aerial tuning inductance and coupling coil (2 500 μH) at 16 000 cycles was 0·11 ohm, giving a decrement of 0·00137 for the coils. These values of decrements are very low and the author has not noticed details in the technical Press of any transmitting inductance which is as efficient as these have proved to be.

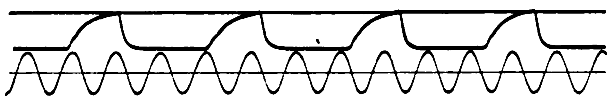

FIG. 20.—Oscillogram of rectified aerial current.
[Aerial current = 515 amps.]

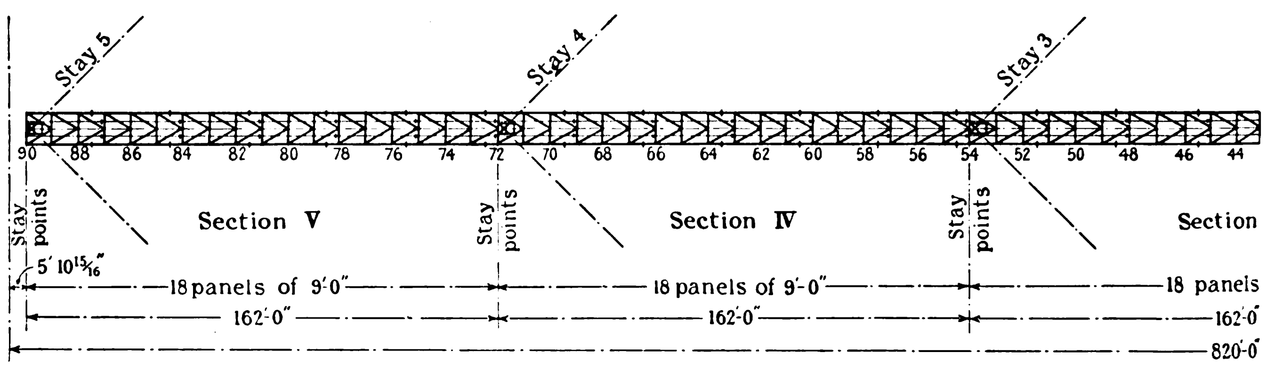

FIG. 21.—Elevation of mast.

RELATIVE POSITIONS OF VARIOUS AMPLIFIERS AND AERIAL CIRCUIT.

Fig. 18 is a section of the transmitting building, showing the relative positions of the power units and their output circuit. It will be noticed that the condensers of the primary circuit and the smoothing condensers on the high-tension d.c. supply are placed on a floor immediately above the power units. A large opening is provided in this floor for light and observation purposes, and the high-frequency leads from the ground floor to upper floors are taken through this.

The inductances for the primary and aerial circuits are mounted on wooden beams above the condenser floor. This arrangement places the inductances as far as possible from the floors, walls, etc. The metal work used in the construction of the building above the condenser floor is reduced to a minimum, and is a negligible quantity.

METHOD OF KEYING AND SHAPE OF SIGNALS.

One of the greatest difficulties experienced in the design of any type of large-power radio transmitter is that of successful keying, and in each case the best method and best adjustment are obtained by experience and experiment. A considerable amount of experimental work on various methods of keying a valve transmitter was carried out with the 50-kW transmitter at the Post Office Northolt radio station, and as a result of those experiments it was decided to provide for the simultaneous operation of a simple "make and break" key at each of the three points in the circuit marked X in Fig. 10. The system has proved to be eminently satisfactory and no difficulties have been experienced up to the highest powers used at present. Creed pneumatic keys are used for points "a" and "b," and a magnetic relay for point "c."

It will be observed that there is no oscillation in the aerial when the key is "up," and that this result is obtained by breaking the feed to the grid from one stage of amplification to the next, as shown in Fig. 19, which is a skeleton diagram of the last inter-stage circuit.

There are two points of particular interest in the arrangement. The first is that the key splits the coupling condenser to the grid and leaves the condenser E between the grid and filament when the key is up. This condenser is of sufficient value to make the impedance from grid to filament capacitative, and this counteracts any tendency that this stage may have to self-oscillate.

The second point of interest is the series circuit A B C from grid to filament. "A" is merely a high-frequency choke, "B" is an adjustable resistance (grid leak) and "C" is a d.c. (grid bias) generator. When the key is down, the mean negative grid potential is the sum of that due to the grid leak and the generator; when the key is up, the only bias is that due to the generator.

By adjusting the proportions of the bias due to grid leak and generator respectively when oscillating, it can be arranged that the generator voltage is sufficient to allow a suitable direct current to pass through the valves when the key is up. The advantages of this are two-fold and are shown below :—

(1) The d.c. load with " key up " reduces the voltage " kick " on the generator with keying.
(2) The conductive path through the valve (due to the small grid bias) increases the damping of the aerial when the key is up, with a corresponding improvement in the shape of the signals.

The latter point is well illustrated by the group of oscillograms in Fig. 20, which shows the shape of the signal in the aerial for a series of dots at about 50 words per minute. The oscillogram of the rectified aerial current obtained from a local circuit shows quite clearly the different rates of change for growth and decay respectively of the aerial current.

From similar oscillograms of the aerial current the decrement of the aerial circuit for the rise of current has been calculated as being 0·0086, whilst for the decay it is as high as 0·024. The advantage of this method

below this are columns of porcelain insulators and a granite cube (5 ft. 6 in. sides), the whole being supported by a steel column the top face of which is 8 ft. 2 in. above ground. The masts are of triangular form with 10 ft. sides, the vertical posts being formed of two channels fastened together at an angle of 60° by a bent bar plate. The bracing is arranged in panels 9 ft. high and is of the K form.

Five sets of stays, 3 per set, are provided and divide the mast into 5 sections.

The mast is not tapered, but the mast sectional members are gradually diminished in size at each stay point from the bottom to the top of the mast.

The principal dimensions of the mast sections are :—

Vertical posts.
Channels—Bottom section, 10 in. × 3½ in. × 28·2 lb.
Top section, 5 in. × 2½ in. × 11 lb.
Bent bar plate—Bottom section, 8 in. × ½ in.
Top section, 6 in. × ⅜ in.
Bracing angles.—Bottom section, 4 in. × 4 in. × ½ in.
Top section, 3½ in. × 3½ in. × ⅜ in.

The masts were designed to withstand a uniform wind load of 60 lb. per sq. ft. of projected surface, and a horizontal antennæ pull of 10 tons at the top. The

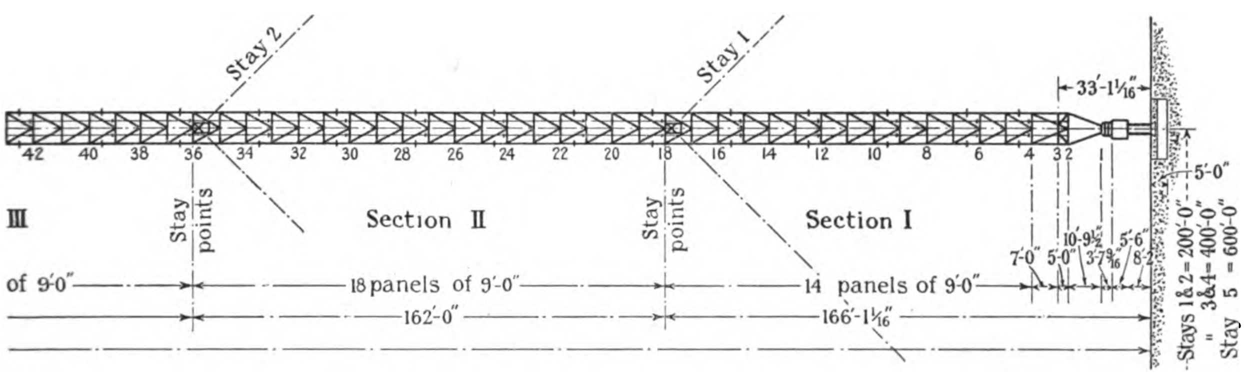

FIG. 21 (*continued*).

of keying as regards shape of signals is therefore quite obvious; the oscillogram indicates that, for higher speeds, advantage should be taken of the quick decay by decreasing the length of the " space " relatively to the " mark," and means for doing this are being developed. This method of keying is due to Messrs. Hansford and Faulkner.

The whole of the work of erecting and assembling the internal wireless plant, including the excitation units, valve panels, power units, oscillating circuits, and the winding and jointing of most of the inductance coils, was done by Post Office workmen under the supervision of, and to the detailed designs of, Post Office engineers. The tuning-fork units were made in the Post Office experimental workshop at Dollis Hill.

Masts.

The masts are 820 ft. in height from ground-level to the top of the antennæ aerial sheave and are of the stayed and pivoted type, insulated at the base (see Fig. 21). The pivot is about 17 ft. above ground-level;

maximum heel or deviation from the vertical allowed under load was 1 per cent, i.e. 8 ft. at the top of the mast. It was specified that the maximum compressive stress in lb. per sq. in. was not to exceed

$$18\,000 - 80\,l/r$$

when l/r is equal to or exceeds 50, and not to exceed 14 000 lb. per sq. in. for ratios of l/r less than 50, where l is the length of the post between bracings, or the distance between stays, and r is the least radius of gyration of post or mast section. Under these conditions the maximum bending moment occurring at any section was 400 tons-ft. and the maximum shear force 15 tons. Throughout the length of the mast below the top stay the compressive load due to the weight of the structure and the vertical component of the stay tensions always exceeds the tensile load due to bending moment, and the posts are therefore always in compression.

The total weight of steelwork in a mast is 170 tons, and the weight of the 15 stays is 28 tons and stay anchorages, etc., 12 tons. Under maximum wind load

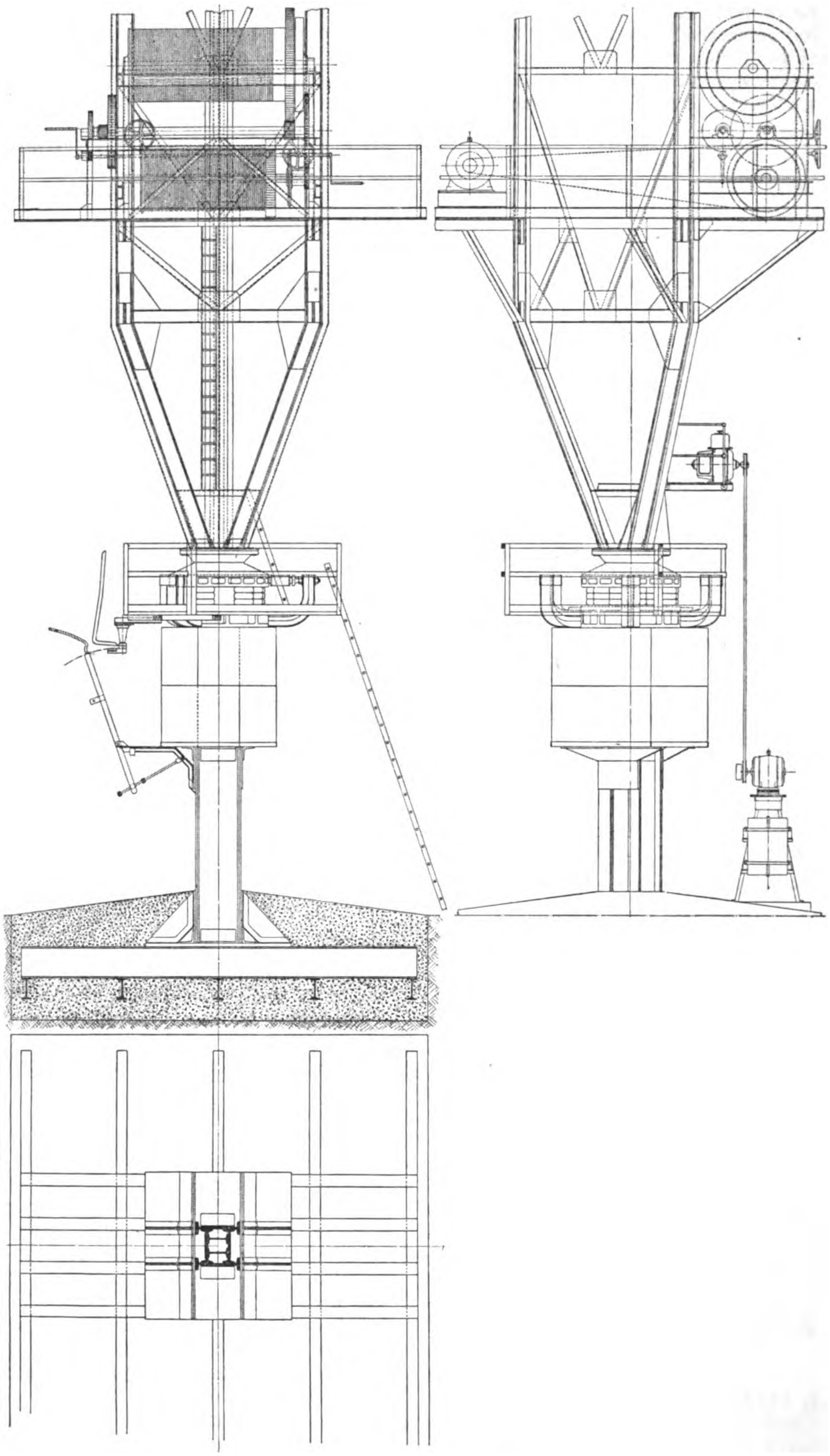

FIG. 22.—Base of mast.

the resultant vertical load on the base of the mast is 400 tons.

The foundations of the mast consist of a reinforced concrete block 20 ft. × 20 ft. × 6 ft. The reinforcement consists of one row of steel joists 18 in. × 7 in. × 75 lb. and a second row of steel joists of 12 in. × 6 in. × 44 lb. placed at right angles to the first row: the steel joists are bolted together and the steel supporting stanchion is bolted to the upper row of joists (Fig. 22).

The maximum load on the earth surface is 1 ton per sq. ft.

Borings were taken at mast positions to depths of about 25 ft. and averaged 1 ft. of soil, 3 ft. to 8 ft. of yellow loam and 12 ft. of soft blue clay, below which was stiff blue clay. In one case only running sand was encountered and the foundations were carried below this to the blue clay.

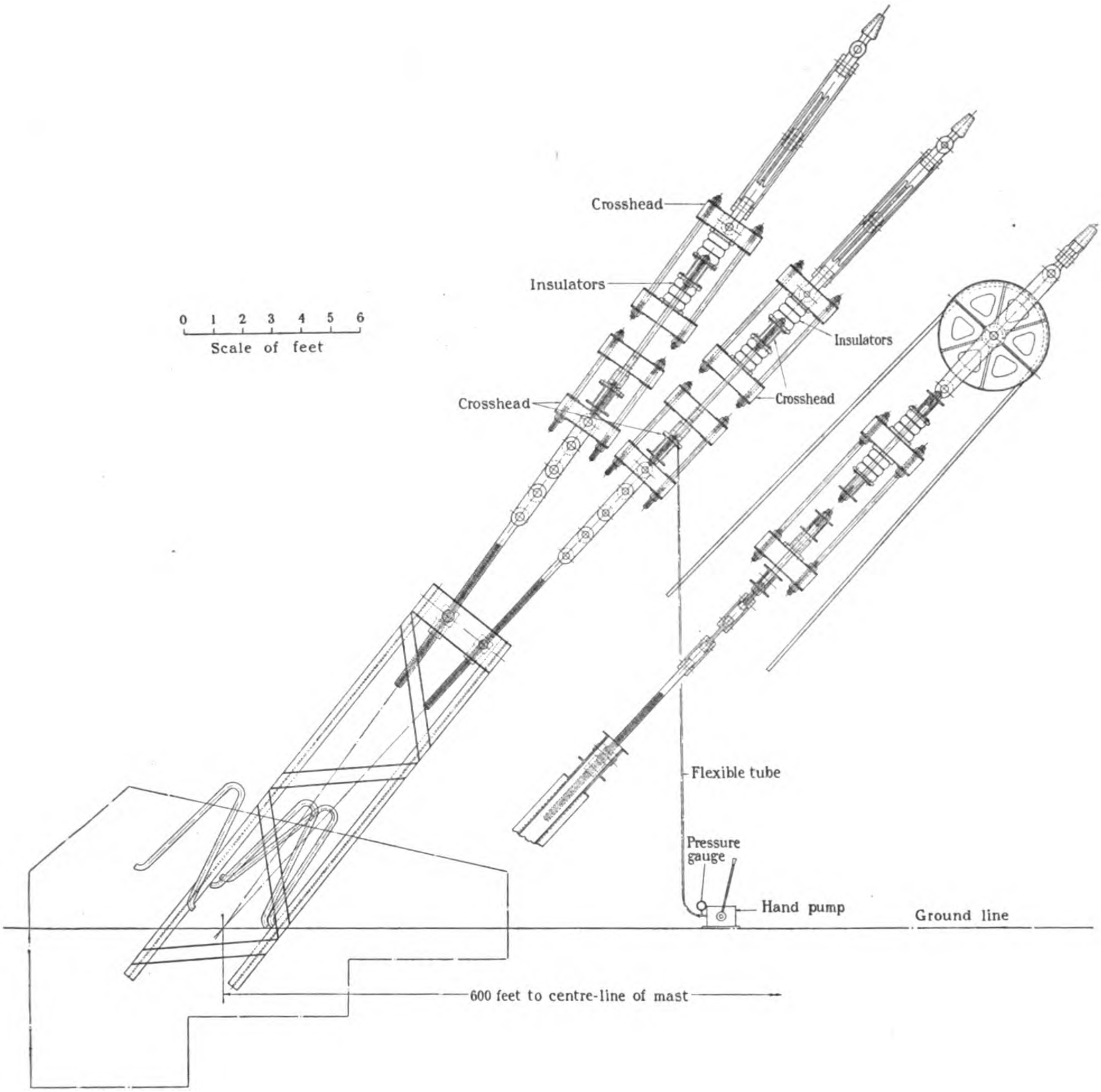

FIG. 23.—Stay arrangement and anchorage.

INSULATION OF THE MASTS.

Two considerations arose in determining the method to be adopted in insulating the masts :—

(1) The choice of a dielectric capable of withstanding a high voltage at high frequency and a considerable compressive load.

(2) Arranging the insulating medium so that the capacity of mast to earth was as low as possible.

The solution arrived at is indicated in Fig. 22. The insulation is primarily provided by 12 columns of porcelain insulators arranged three in each column and placed between steel castings immediately below the pivoted joint. These insulators comply with the specified conditions of withstanding a high-frequency voltage of 25 000 (R.M.S.) at 50 000 cycles per sec. for 6 hours without overheating or breaking, the insulators having first been immersed in water for 2 hours. They were tested mechanically to a compression load of 270 tons, corresponding to a factor of safety of 6.

Each insulator is 9 inches in diameter and 3½ in. thick, with a recessed hole in each face 2½ in. diameter and 1 in. deep.

To ensure uniform distribution of stress between the columns all insulators have ground faces and those in each column were cemented together by a thin layer of Portland cement.

Wooden blocks were used in the place of the insulators during the erection of the masts. To insert the insulators, the mast was raised on hydraulic jacks, the wooden blocks were removed and the columns of insulators inserted with a thin layer of cement at the bottom. The mast was then lowered on the insulators, but the full load was not taken off the jacks until the cement had properly set.

It will be noted (see Fig. 22) that the arrangement of the insulators permits of the insertion of 3 hydraulic jacks to raise the mast and replace any damaged or faulty insulators as required.

The stays are insulated at the base only. The same type of insulator is used as for the mast base, the method of mounting being indicated in Fig. 23. The insulators are in compression, the top column taking the load and the bottom acting as steadying insulators. A hydraulic press is incorporated in the stay-rope attachmen and can be connected to a hydraulic pump and gauge on the ground and used to measure directly the tension of the stay.

The stays are of parallel strand construction and were made on the site. The maximum tensions imposed on the stays under full wind load vary from 30·5 to 37·6 tons in the different stays, the top and bottom sets carrying rather higher loads than the intermediate, and two sizes of stay ropes were adopted. The larger is composed of 151 wires of No. 10 S.W.G. having an area of 1·918 sq. in. and a circumference of 5½ in., and the smaller of 103 No. 10 S.W.G. and 6 No. 8 S.W.G. The factor of safety specified for the stay ropes was 4.

The individual wires of No. 10 S.W.G. have an extension, within the elastic limit, of 0·5 per cent under a stress of 57·7 tons per sq. in., and a breaking load of 3 050 lb.

The aggregate breaking load of the larger ropes, assuming uniform distribution on all the wires, would be about 205 tons. Short lengths of rope with sockets attached were tested in connection with experiments carried out to determine the best type of socket, and the ultimate strength of the rope was greater than 125 tons, the limit of the machine available for the tests. This type of stay has a great advantage over the usual small wire stranded variety in possessing a smaller extension under load. The parallel-strand type has an extension very little in excess of that of the individual wires and, for the longest stay in use on the Rugby masts, this, under maximum load, does not exceed 17 in. irrespective of variations due to temperature, or, allowing for a temperature-rise of 50 deg. F., 21 in. The best results obtained on stranded ropes of special construction and under similar conditions would be equivalent to 35 in. extension for the longest stay at Rugby.

The advantage of the use of the parallel-strand construction is thus evident in limiting the heel of the mast under conditions of load. A further advantage of the use of parallel-wire ropes is that a more exact determination of stay stresses is possible. The masts were manufactured and erected by Messrs. Head Wrightson and Co.

Switches of substantial design are provided for earthing the masts when access to them is required and also for enabling transmission to be carried out at full power with the masts earthed. A spark-gap is also associated

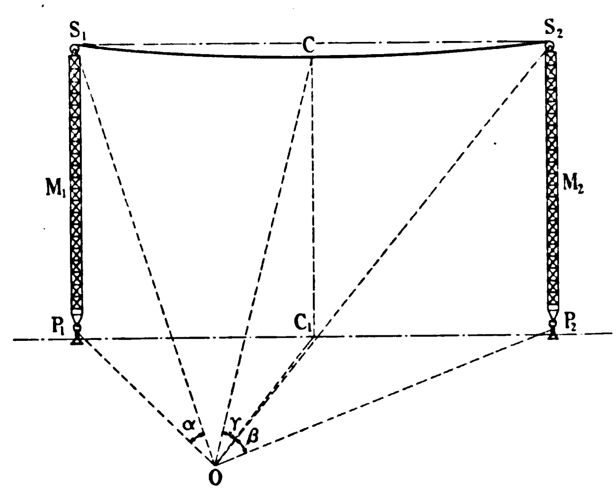

FIG. 24.—Method of load-testing masts.

with the switch as a protective device against abnormal voltages on the masts or aerial.

In order to test the masts with the specified horizontal pull of 10 tons applied at the top, a steel rope was suspended between two masts and hoisted by means of the permanent mast winches until the required tension was reached. Fig. 24 illustrates the method employed. P_1 and P_2 are the vertical projections on the ground of the ends of the rope S_1, S_2, suspended between the masts M_1 and M_2. A theodolite was fixed at O such that the length $OP_1 = OP_2$. The angles of elevation α and β of S_1 and S_2 were measured accurately, and also the angle of elevation γ of the lowest point C of the steel cable. It was then a simple matter to measure the angle P_2OC, in the horizontal plane, C_1 being the vertical projection of C. Also the angle C_1P_2O = angle C_1P_1O being known, and the length OP_2 having been accurately measured, the distance OC_1 was calculated. Thus it was possible to calculate the values of $S_1P_1 = OP_1 \tan \alpha$, $CC_1 = OC_1 \tan \gamma$, and $S_2P_2 = OP_2 \tan \beta$, and so obtain the dip d of the cable. The mass per foot of the steel rope, w,

and l, the distance S_1S_2, being known, the horizontal tension

$$T = \frac{wl^2}{8d}$$

was obtained.

A check on the aerial dip was also made by the same methods. The current taken by the electric motors of the winches, however, was found to give readings consistent with the value of the tension in the aerial suspending halyards and, during the erection of the aerial, reliance was placed upon these readings.

Mast and Aerial System.

The mast and aerial system are arranged so that two separate aerials of different capacities may be used or alternatively the two combined to form one larger aerial (Fig. 1). Two of the masts, spaced symmetrically with regard to the station buildings and 1 320 ft. apart, are common to both aerial systems. The larger of the two aerials is the telegraph aerial and is supported on 8 masts arranged to form an elongated octagonal figure in plan, with sides of 1 320 ft., but with opposite sides on axes at right angles at distances apart of 880 yards and 1 210 yards.

The smaller aerial is supported on 6 masts with the same spacing but forming an aerial with two open arms. This arrangement is designed to permit of the addition of four more masts if necessary, for which purpose sufficient ground is available.

Each aerial system is fed by a lead-up connected to two separate feeders, one attached to each of the masts nearest to the station. When using the whole system as one aerial the leads-up to the two separate aerials are connected together by an internal cable running the whole length of the inductance room.

The aerial insulators are of the porcelain-rod tension type, weighing 6½ cwt. and are shown in Fig. 25. The specified testing pressure which the insulators had to withstand was 120 000 volts at a frequency of 50 000 cycles per second.

Each porcelain tube of the aerial insulator was tested to a load of 10 tons. The complete insulator will thus withstand a pull of over 20 tons. Electrical tests made previous to erection showed that 200 000 volts at 50 000 cycles per second could be applied across the ends without damage. The insulators were made by Messrs. Bullers, Ltd.

Spider spreaders of tubular steel, 12 ft. in diameter, and spaced 140 ft. apart, are used to support the eight 7/14 S.W.G. silicon-bronze wires that form the cage aerial. In order to reduce the dip of the aerial, it was essential to design spreaders having small mass without undue sacrifice of strength. The type decided upon, as best meeting these requirements, is shown in Fig. 26. The split hubs of each spreader are tightly clamped to a central steel supporting cable. All radial arms and circumferential ties are composed of weldless carbon steel, containing about 0·5 per cent of carbon, with a yield point of 30 tons per sq. in. and an ultimate breaking stress of 40 tons per sq. in. In spite of their light structure the spreaders have withstood the severest gales without apparent damage. At each mast the aerial insulator is attached to the steel wire cable at the junction of two spans of the cage aerial, and the aerial is held in space well away from the metal masts.

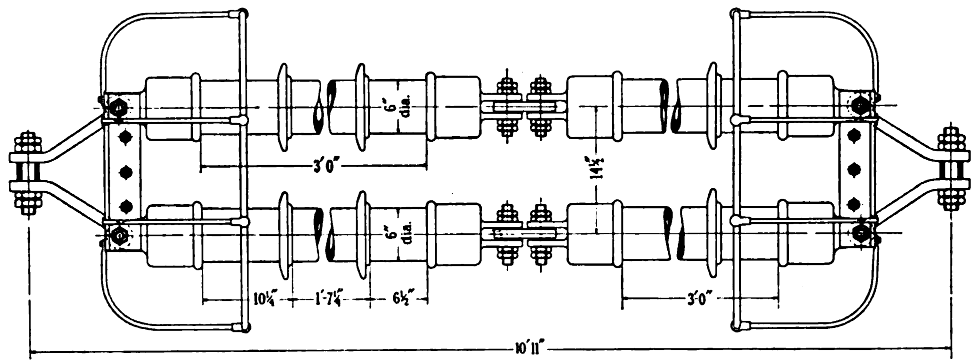

Fig. 25.—Aerial insulator. Scale ⅜ in. = 1 foot.

The two 8-wire feeders are formed on spreaders 6 in. diameter spaced 20 ft. apart. They meet at a point about 400 ft. from the building and are joined to form a single 16-wire lead-up on 6-in. spreaders. The tension of the lead-up wires is taken by six porcelain tubes, similar to those used in the main aerial insulators, suspended on a steel structure near to the building. The six tubes are arranged to form three arms 120° apart, each arm comprising two tubes in series. From these strain insulators, the lead-up wires pass through a copper tube about 19 ft. long that bridges the space between these insulators and the transmission building. At the building the tube carrying the lead-up wires passes through the middle of a double conical porcelain insulator fixed at the centre of a glass plate, 7 ft. square, and the lead-up wires then pass from the tube to the aerial tuning inductance.

In order to avoid either the overloading of the mast or the breaking down of the aerial, the steel rope supporting the aerial insulators passes down the centre of the mast and is attached to a drum fitted with a slipping friction brake so adjusted that the rope is slackened when the load exceeds 10 tons.

The earth system on the telegraph site consists of

copper wire, 100 lb. per mile, buried a few inches below ground. The earth follows the plan of the aerial and extends 800 ft. on either side of the vertical projection of the aerial on the ground, as shown in Fig. 27. Near the buildings the wires leave the ground and converge upon the transmitting room in a fan arrangement.

An insulated counterpoise has been erected under the smaller aerial at an average distance of about 16 ft. from the ground. The counterpoise follows generally the earth system in arrangement, except that the spacing between individual wires is not uniform but varies from 40 ft. immediately below the cage aerial to 80 ft. at the edges.

Observations have been made on the effectiveness of the insulation at the base of the mast by comparative measurements of the aerial resistance and the effective height with the masts insulated and connected to earth.

These observations show that the ratio of the effective height of the aerial with the masts insulated, to the effective height with the masts earthed, is 1·22. The effective height with masts insulated as deduced from measurements made at Wroughton near Swindon is approximately 185 m (607 ft.). The mean geometric height of the top of the aerial at Rugby is 820 ft. – 45 ft. (average dip of aerial) = 775 ft.

The effective height with the mast insulated is therefore 607/775 = 0·785 of the mean geometric height, or 607/820 = 0·74 of the mast height.

Fig. 28 gives the resistances of the aerial with masts insulated and masts earthed respectively. At 19 000 m wave-length the aerial resistances with the masts insulated is 0·7 ohm, and the aerial resistance with the masts earthed is 0·55 ohm.

Fig. 29 shows that the use of inefficient insulators for the masts practically doubles the aerial resistance. Such inefficient insulation is obtained when the porcelain insulators only are short-circuited and the granite blocks alone are used as insulators.

The larger telegraph aerial constants with the mast insulated are: wave-length 7 930 m, capacity 0·0334 μF, and equivalent inductance 530 μH.

To enable overhauls and examination of masts to be made, it is desirable to be able to transmit with a particular mast earthed, as work on an insulated mast is impossible during transmission. The curves in Fig. 30 indicate the effect on the larger telegraph aerial resistance of earthing either No. 1 mast (which is nearest to the station) or No. 6 mast (which is at the end of the aerial).

The d.c. insulation resistance of a mast to earth, including all stay insulators, varies between 1·5 and 3 megohms according to weather conditions.

The insulation resistance of the whole aerial to earth with masts insulated is 8 megohms.

The resistance of each granite block is approximately 20 000 ohms, but the value steadily rises as the granite slowly dries out. The effect of the dielectric current in the granite is to drive out moisture gradually from the interior. This action, combined with absorption by

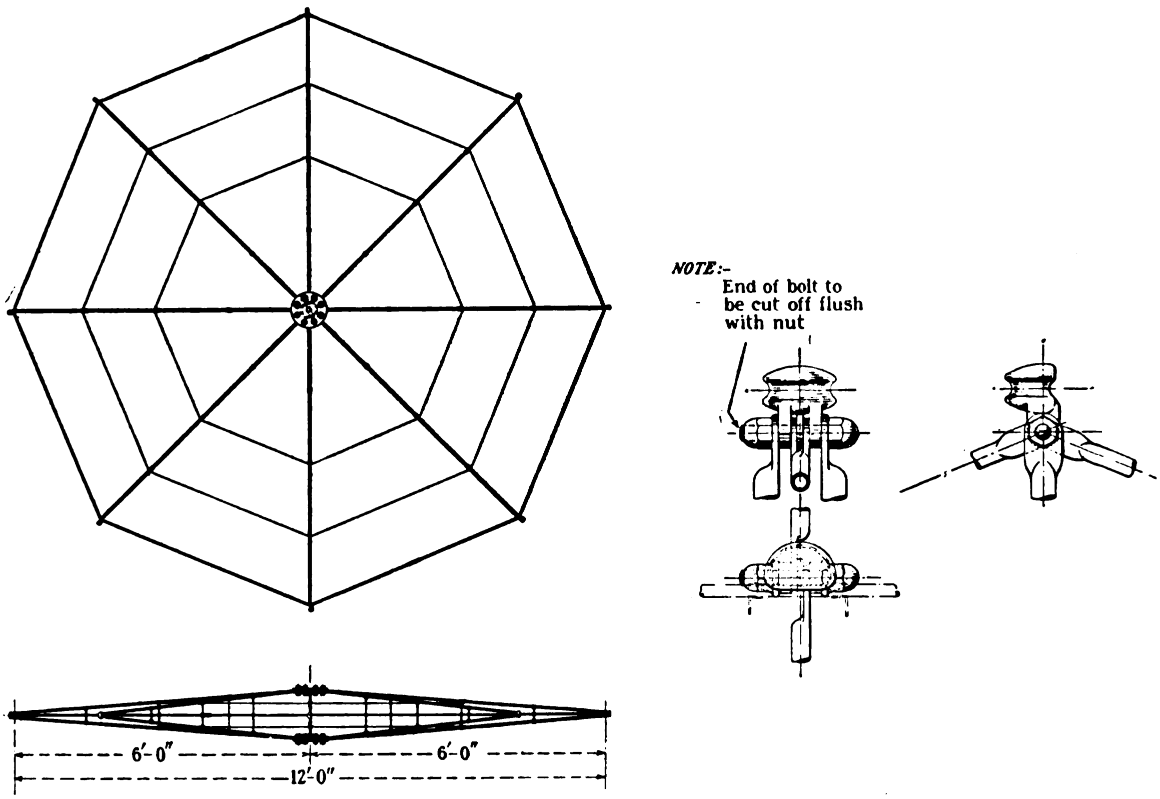

FIG. 26.—Aerial spreader.

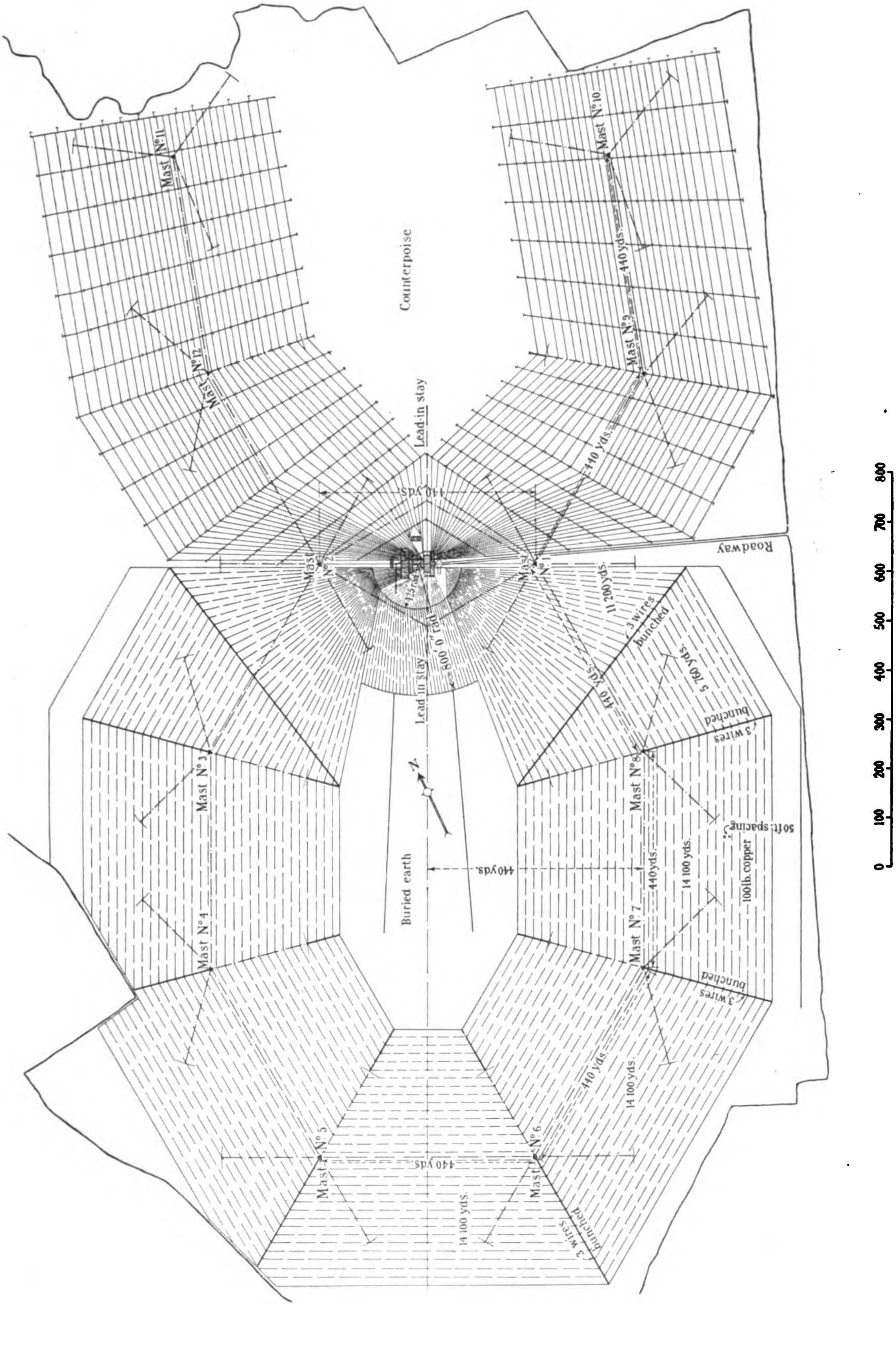

FIG. 27.—Earth system.

the atmosphere in the spring and summer, will raise the insulation to a maximum value and the granite blocks will then be completely coated with bitumastic solution to retain them in a dry state. Bitumastic solution has been tried experimentally for this purpose

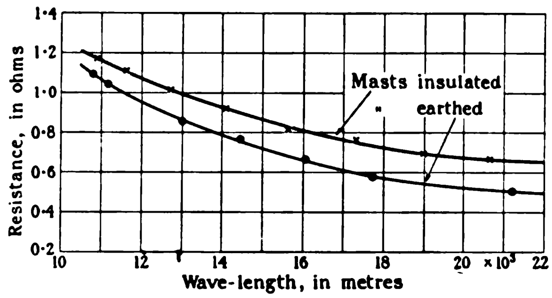

FIG. 28.—Curves of aerial resistance with masts insulated and earthed, respectively.

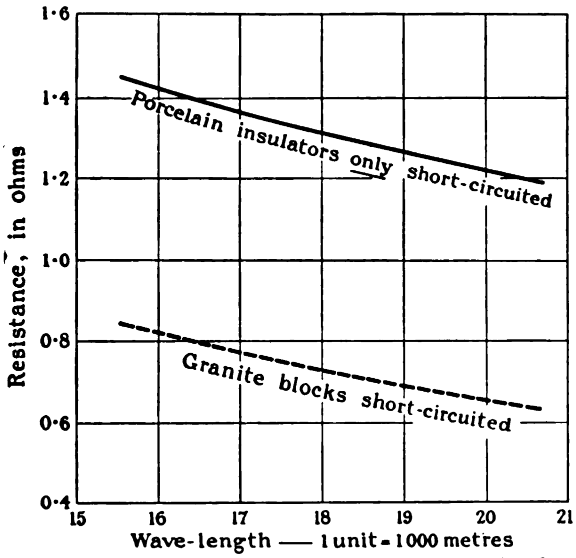

FIG. 29.—Curves of 8-mast aerial resistance with insulators partly short-circuited.

Tests taken first week in November, 1925. Ohmic resistance of each granite block = 12 000 ohms. Ohmic resistance of porcelain insulators under each mast = 3 megohms.

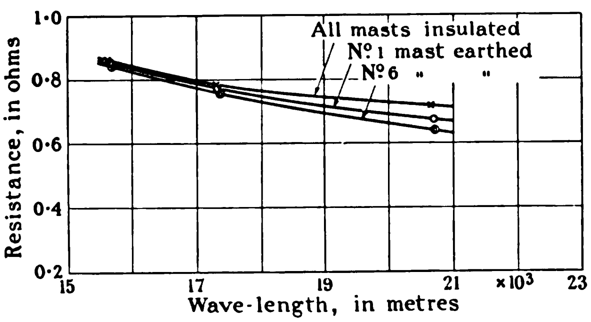

FIG. 30.—Curves of aerial resistance, earthing separate masts.

and proved to be satisfactory. The method outlined for slow drying under working conditions was decided upon as the results of tests made on granite specimens and in order to obviate the risk of moisture remaining in the granite if the blocks were coated with bitumastic solution before erection.

The voltage-drop across the mast insulators was found to be 12 000 volts and the drop across the stay insulators 12 300 volts with an aerial voltage of approximately 165 000, corresponding to an aerial current of 550 amperes.

Curves of the resistance of the smaller telegraph (telephone) aerial and counterpoise are given in Fig. 31. In order to obtain information, measurements were taken both before and after the far ends of all the wires of each arm of the counterpoise were connected together. The smaller telegraph (telephone) aerial constants are: wave-length 4 850 m, capacity 0·0164 μF, and equivalent inductance 394 μH.

Cooling Pond.

A stream running through the site is utilized to supply the cooling water, and a ferro-concrete cooling pond capable of storing 500 000 gallons of water was constructed by direct labour.

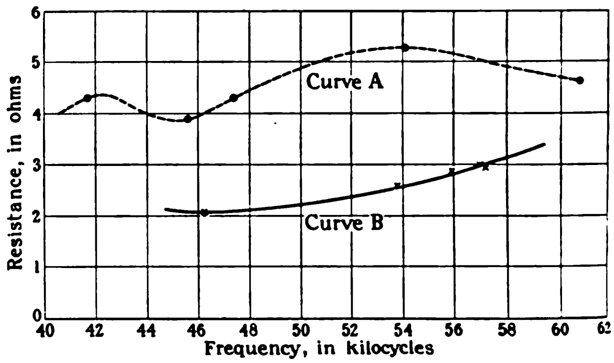

FIG. 31.—Resistance curves of telephony aerial.

Curve B shows the effect of joining together the ends of all the wires of each arm of the counterpoise. Counterpoise insulated in each case. Insulation resistance about 60 000 ohms.

General Results Obtained to Date.

The following schedule gives two typical series of measured values of the more important quantities when working on one portion of the aerial only, viz. that having a capacity of 0·033 μF.

Number of power units in use		3	3
Total number of valves in power units ..		54	54
Aerial circuit	Current	550 amps.	600 amps.
	Power ..	257 kW	306 kW
Primary circuit current		275 amps.	300 amps.
Coefficient of coupling to aerial		0·015	0·015
Efficiency of coupled circuit..		97½ %	97½ %
D.C. Input	Voltage ..	5 820 volts	6 780 volts
	Current ..	61 amps.	64 amps.
	Power ..	355 kW	434 kW
Filament power.. ..		48 kW	48 kW
Efficiency of transmitter	Excluding filament..	72 %	71 %
	Including filament..	64 %	64 %
Voltage on antenna ..		165 000 volts	180 000 volts

These figures are for about two-thirds power of the station, the present limitation being the fact that only a portion of the main aerial is available, which portion is already being used at antenna voltages in excess of **165 000.** With this power, however, the station has been proved to have a world-wide range and only the collection and scrutiny of data over a long period will show to what extent, if any, an increase of power is necessary for a *continuous* world-wide service. From the experience already gained it can be predicted that, if it is proved to be necessary, 3 power units using a d.c. supply of about 9 000 volts will be able to give an antenna current of the order of 750 amperes in the larger antenna of $0 \cdot 045\,\mu$F, with an increased overall efficiency.

It is interesting to note that during the several months that the telegraph station has now been testing and working commercially with type D circuit, not a single complaint has been received in regard to interference with broadcast or other reception by harmonics from the telegraph transmissions, and, moreover, broadcasting stations have been received, without interference, on the site under the aerial.

Experimental Telephony Installation.

The experimental telephony installation is smaller than the telegraphy installation and works with the smaller aerial. It utilizes the American Telephone and Telegraph Co.'s " single side band " system described by the late Dr. H. W. Nichols.* The modulating and filtering circuits and the valve amplifying panels were made and installed by the Western Electric Co., Ltd., in co-operation with the American Telephone and Telegraph Co.

* *Journal I.E.E.*, 1923, vol. 61, p. 812.

From the 31st January to the present time, a period which covers the best radio transmission conditions in this country, experimental week-end tests show that good speech is received in New York during most hours of the day when using an aerial current of about 185 amperes. This installation may form the subject of a separate paper when reliable data has been collected over the period of bad atmospheric conditions.

In addition, two other installations to work with smaller aerials supported on the existing masts are being provided. One will be a medium-wave 50-kW valve set and the other a short-wave 15-kW valve set.

Conclusion.

As liaison member between the Wireless Telegraphy Commission and the Post Office the author would like to remark on the cordial collaboration which existed between the Commission and his engineers throughout the progress of the work, and in conclusion he desires to acknowledge the valuable help received in writing this paper from the Post Office Engineers directly responsible for the various sections of the work, namely Mr. A. J. Gill on the power plant, Mr. R. V. Hansford on the wireless plant, and Col. A. S. Angwin and Mr. T. Walmsley on the masts, aerials and external plant.

Discussion before the Wireless Section, 14 April, 1926.

Sir Guy Wrightson: A description of the masts and the various difficulties we experienced in erecting them was the subject of a recent paper read before the Institution of Civil Engineers by Col. Angwin and Mr. Walmsley. In that paper I think there was only one interesting point omitted, viz. the weather factor. This work took place during an extremely wet and windy season and we were very lucky in having not a single accident in working at those great heights in very windy weather.

Mr. C. F. Elwell: The Post Office engineers have advanced valve practice to such an extent that no other valve station has anything like the power of the Rugby station. In view of the possibility of the erection of further stations of this type and power there are two points to which I should like to draw attention. The first is the question of the number of masts. Is it necessary to erect so many? There are no engineering difficulties in the way of erecting even higher masts, nor are there any difficulties in the way of providing for much greater aerial pulls—for example, 30 tons. In this case probably the masts could have been spaced double the distance apart. This is only an idea for the future. The question of economics has to be studied, but I believe that probably half the masts could have been erected with each one a little higher; this would have compensated for aerial sag, and have enabled a little money to be saved. The other point is the multiplicity of small valves. Personally I believe in the future of single units. Such a unit would no doubt be of a type which would have its own pumping outfit. We are at present in the possession of very little data as to the maintenance of small valves. In the case of a single valve I think it is quite possible to renew its filaments and generally keep it in order at the cost of certain spare parts.

Mr. P. P. Eckersley: I think that any criticism that might be put forward falls to the ground entirely when it is realized that even as far back as 5 years ago the Commission were bold enough to back their preference for valve work, which was then considered, by even the greatest enthusiasts, somewhat dubious for high-power stations. Finally, they have applied real engineering practice and technology to the production of high-frequency currents. I think they are to be congratulated on this account above all others. The tuning-fork drive is, I think, a unique advancement, as everyone must admit that the great aim of the future, both in broadcasting and in telegraphy, must be towards the maintenance of a constant wave-length. It may be of interest to mention that the British Broadcasting Co. also has had some experience of producing harmonics from tuning-forks and using them as independent drives. Starting with a frequency of something like 890 periods per sec., we have been able successfully to drive a particular station at a frequency

of nearly 1 million. Referring to Mr. Elwell's remarks on valves, I suggest that the Post Office engineers have taken the safe course. I should like to ask the author whether the economic gain resulting from insulating the masts could not also have been obtained by employing a somewhat greater power. Apparently the insulating of the masts was an expensive and difficult engineering task involving considerable experimental work, and it would be interesting to hear whether the author is of the opinion that the same result might have been obtained by omitting the mast insulators and providing a larger aerial current to compensate for any reduction of energy actually radiated. We shall all await with great interest the development of the transatlantic telephone experiments.

Mr. G. Shearing: The Rugby radio station represents the most ambitious undertaking in thermionic valve wireless-telegraph transmission up to the present. Its erection must have been a problem of extreme interest, for the task of building complete a high-power valve transmitter such as this, with practically no limitations, is one which comes the way of few radio engineers. The high oscillatory power obtained by the use of thermionic valves is, I venture to think, very gratifying to all who have been engaged in the experimental development of high-power valves. In view of the application of shorter wave-lengths below 100 m at the present time to long-range transmission, and the remarkable results one can obtain with relatively small power supply, it is not easy to say whether the Rugby station is the climax of high-power long-wave valve transmitters; and the trend of wireless telegraph development in the next few years will be a matter of great interest to us all. With regard to the power supply from the substation at Rugby, I should like to know if the line drop to the radio station is negligible or whether the automatic regulators compensate for line drop at varying loads. It would be of interest if the author could give us the load characteristics of the high-tension d.c. generators. Concerning the adoption of motor-generator sets for the high-tension supply by the Wireless Telegraphy Commission in 1922, I am wondering if the author is still of the same opinion, as thermionic rectifying valves can be obtained of good efficiency and on the whole of greater reliability than transmitting valves of the same anode rating. Possibly some economy might result from the adoption of thermionic apparatus for both transmitter and high-tension supply. On the other hand, there is the question of the interposition of the inertia of a mechanical link between the supply undertaking and radio apparatus for the high-tension generator to reduce fluctuation of the supply power during signalling, as opposed to a purely electrical link for the static high-tension transformer and thermionic valve rectifier unit, unless an a.c. generator and motor is introduced also for the h.t. transformer supply. With regard to the adoption of a frequency of 100 for the valve filaments, would not a higher frequency, say of the order of 250, have been better when introducing the motor plant? This would reduce considerably any cyclic temperature fluctuation of the valve filaments as compared with that produced by the small change in frequency from 50 to 100. With reference to the transmitting valves, the designed power dissipation per valve from the figures on page 690 is of the order of 460 kW, or about 8·5 kW per valve, and the test-figures on page 708 correspond to an average anode dissipation of nearly 2·4 kW per valve during marking (I assume the static dissipation is less than this; perhaps the author will say what is its value), so that the valves at present are being operated at a fairly conservative anode power rating as compared with the continuous rating of 10 kW of which each valve is capable. In this connection, is it easy to arrange for the valves to share the load equally? If not, is it possible to correct by filament adjustment alone or are other adjustments necessary; also, have the valves any repair value after breakdown? The inductively coupled circuit of type A (Fig. 16) is undoubtedly inferior to the capacity-coupled arrangements described in the same figure, but for the cases where rapid wave-change over a wide range renders its use desirable, a great reduction of harmonic interference can be obtained by the insertion of a rejector type of circuit between the anode tapping and earth. This is, of course, equivalent in effect to the introduction of a capacity circuit to earth to provide an easy path for the harmonics. The harmonics generated on the Rugby wave-length which may cause interference in general to broadcasting apart from Daventry, are those around the 40th harmonic of the fundamental, and it would be of interest to know whether any radiation has been observed on the lower harmonics such as the 2nd, 3rd, etc. It would also be interesting to obtain an oscillograph curve showing the change of the anode current through the valves during signalling, for comparison with the curve of rectified aerial current given in Fig. 20 of the paper.

Mr. R. N. Vyvyan: The Marconi Co. have been designing high-power stations for Imperial communication on long wave-lengths for a great many years. Actually we designed a station only a short time ago on the valve system to give 875 amperes in an aerial supported by masts approximately as high as those at Rugby. That station was not completed, however, owing to the introduction of the short-wave beam system. I think it is certain that the Rugby station is the last word in high-power wireless stations, in two senses. It is excellently designed in every respect and, in my opinion, reflects great credit on the Post Office engineers, but I do not think that any more super high-power stations will be built, since long-distance communication will, I believe, in future be carried out only by the short-wave beam system. That is also the opinion of my company, but we shall know in a very few weeks whether that opinion is sound or not.

Mr. W. T. Gibson: The author mentions that distilled water is used for cooling the valves. He points out one advantage of this, and I propose to give another. The point he mentions is the very high resistance obtained with the water, giving a leakage current of only 20 mA at 10 000 volts, or 200 watts power loss. With ordinary domestic water the leak would probably be 20 or 30 times as great. That does not matter much in small stations utilizing one or two valves, but with a station of the size of Rugby it becomes very important and there would probably be a loss of 4 or 5 kW in the

hose pipe. The other interesting point in connection with distilled water is that there is no deposit in the anode, whereas it is a matter of experience with ordinary commercial water that quite a considerable deposit is formed on the anode at places where it gets warm. That would become very serious and might create serious maintenance problems in removing the deposit at frequent intervals. The layer is a good insulator and a very bad conductor of heat, steam is formed underneath the anode and possibly overheating of the anode occurs. I agree with Mr. Elwell that in the future there will be a development in the size of valves, but I do not agree with him that the demountable valve is the valve of the future. The great thing is to have a valve of absolutely stable characteristics, and I believe that these are extraordinarily difficult to obtain with a valve that is permanently connected with the pumps. There are always slight traces of gas and the pressure is always fluctuating slightly, and that presents great difficulties in operating a large station. Those difficulties, I think, outweigh any advantage in being able to take the valve apart and re-assemble it.

Prof. J. K. Catterson-Smith: I presume that the aerial constants given on pages 706 and 708 are the fundamental natural wave-length and the equivalent capacity and inductance at this wave-length. The equivalent inductance of the smaller aerial, given in the advance copies of the paper as 994 μH, appears to be wrong. Should not it be 394 μH? There is apt to be some confusion as to the exact meaning of such aerial constants, and therefore it might be helpful to state that for these aerials the electrostatic capacities are 0·0524 μF and 0·0258 μF, and the static inductances 832 μH and 618 μH, for the larger and smaller aerials respectively. I notice that the resistance of the larger aerial is plotted, in Fig. 28, for wave-lengths down to 10 800 m, and I should like to know whether these observations were made with lower values of the aerial tuning inductance than the minimum of 900 μH given in the paper. In the case of this aerial, for which the equivalent inductance is stated to be 530 μH and the capacity 0·0334 μF, the effective inductance is $(1/\sqrt{2}) \times 530 = 375\,\mu$H, and the effective capacity is $\sqrt{2} \times 0{\cdot}0334 = 0{\cdot}0471\,\mu$F, so that the range over which the aerial can be tuned with the 900 to 4 000 μH aerial tuning inductance, and neglecting the coupling coil, should be :—

$$\text{from } \lambda = 59{\cdot}6\,\sqrt{[(375 + 900)\ 47{\cdot}1]} = 14\,500\text{ m}$$
$$\text{to } \lambda = 59{\cdot}6\,\sqrt{[(375 + 4\,000)\ 47{\cdot}1]} = 27\,000\text{ m}.$$

Although efficiencies for the transmitting apparatus are given on page 708, I find no statement of the aerial efficiency, which is an equally important matter. Adopting the value of the effective height given on page 706 (viz. 183·5 m) the radiation resistance of the larger aerial works out as 0·158 ohm at 18 350-m wave-length, for which Fig. 28 gives the measured resistance as 0·72 ohm with the masts insulated. The aerial efficiency is then 0·158/0·72, or 22 per cent, a figure which does not compare too favourably with published values of the efficiency of multiple-feeder aerials. I suppose that aerials of the latter type were considered before the final decision was made to adopt the present form of aerial at Rugby. I should like to take this opportunity of suggesting the sending of special test-signals similar to the "U R S I" transmissions, in order that distant measurements could be made over considerable periods. Such observations would, I am sure, be undertaken by a number of laboratories and the results, when collected, would probably afford matter of interest on this class of transmission. We make daily observations of signal strength at Bangalore and would welcome the possibility of recording and measuring the field strength of systematic signals from Rugby.

Dr. W. H. Eccles (*communicated*): I speak as Vice-Chairman of the Wireless Telegraphy Commission which was instructed by the Government to prepare the general design of the Rugby wireless station and to advise during erection. The author was a member of the Commission and also head of the body of engineers who installed the plant. It is largely due to him that the co-operation between those responsible for the general design and those responsible for the construction was so perfectly cordial. I think it would be hard to find an example of a very big job involving innumerable departures from traditional methods in which the team work has been so good. This has helped to ensure success; a success which could not have been achieved without the aid of the able staff which the author has gathered round him at the Post Office. This staff has been responsible, for example, for the development of the method of controlling the wave-length by a tuning-fork, for the design of the valve panels and safety devices, for the calculation of the unusual form of intermediate circuit and tuning coils, for the erection of the very unusual type of antenna, and for the testing of electrical materials by new methods. But the best testimonial to the efficient work of the erecting engineers is the fact that the station has given magnificent performances during its tests and that its erection was completed without any failure, fault or accident. As may be imagined, the volume of business involved in the purchase of the plant and materials for the station was enormous; and although this side of the work is not described in the paper, I think I may be permitted to say that the author shouldered most of the burden and that the estimates were very closely in accord with the final expenditure.

Mr. E. H. Shaughnessy (*in reply*): Mr. Elwell raises the question of utilizing a smaller number of higher masts. Calculations made at the time the estimate was prepared indicated that the number, height and aerial-pull chosen were the reasonable constructional and economical limits. It cannot be said that a valve with a 10-kW output is a small valve; no reliable larger-powered valve was commercially available at the time the station was designed. The Post Office has very little data as to the maintenance and repair of small valves, and no data at all regarding valves with over 20-kW output. Attention is drawn to sub-paragraph 3 (*b*) in the section headed "Considerations in regard to the size of power units."

I am glad to hear from Mr. Eckersley that the British Broadcasting Company is following the Post Office example of producing constant wave-length from a tuning-fork. With regard to using additional valves

and increased aerial power instead of increasing the effective height of the aerial, owing to corona and voltage limits on the aerial and aerial insulators, the matter is not so simple when dealing with such powers as that used at Rugby.

The various points raised by Mr. Shearing were all considered in the design stage of the Rugby station. The use of 100 cycles for the filament supply was adopted, not for the sake of changing frequency but in order to simplify regulation by the use of a motor-generator and Tirrill regulator. The cyclic temperature-variation effect is overcome by balancing the valve filaments in use over the three phases, as explained in the paper. The choice of 100 cycles was made in order to obtain a standard frequency-changing machine which could be delivered quickly. The rating of the valves is in terms of the anode voltage, output and dissipation, each valve being limited to a maximum output or dissipation of 10 kW. Thus it is not permissible to operate the valves beyond the rated anode voltage, output or dissipation. The figure of 1 000 kW quoted is the machine rating; the input to the power units for 540 kW output when working at 72 per cent efficiency would be considerably below this figure. The present static dissipation on "space" is 1 kW per valve. Provided that the precautions specified (page 694) for the operation of valves in parallel are adopted, the valves share the load equally. It will be appreciated that Rugby is essentially a fixed-wave-length station and, in consequence, the time required to change wave-length does not arise. For this reason a coupled circuit was provided which gives a much more efficient anti-interference arrangement than rejector circuits, etc. Observations so far made on harmonic radiation show that there is no radiation on the lower harmonics. Additional oscillograms showing the rise and fall of the various currents and voltages during keying will probably be published at a later date.

Mr. Vyvyan will be the first to recognize the difference between designing a station to give 875 amperes in the aerial and erecting a station that actually has that aerial current. The absolute need for a high-power station in this country which has a simultaneous broadcasting Empire-wide range has been met by the erection of the Rugby radio station. I think it is too early to conclude that no more high-power stations will be built. Our experience of low-power short-wave stations is that they form valuable adjuncts to high-power stations, being able to work for a limited number of hours per day but not regularly at the same time or for the same periods. As beam stations are directional it would require a large number of these to cover Empire broadcasting, and as no beam station has yet been completed or tested I am quite unable to form any opinion as to its superiority or otherwise over ordinary short-wave stations.

As Mr. Gibson points out, it was with a view to avoiding deposit on the anodes that distilled water was adopted for valve cooling at Rugby. The need for this is emphasized when such a large number of valves are being run in parallel.

I have to thank Dr. Eccles for his generous contribution to the discussion.

With reference to Prof. Catterson-Smith's communication, it is, of course, very difficult to quote definite figures of capacity and inductance for a given aerial without making a large number of reservations as regards frequency, etc., on account of the distributed nature of the capacity and inductance. For practical purposes, the values, C_a, L_a, required are those which will give approximately correct results for a reasonable working range of frequency for the calculation of the wave-length with varying values of loading inductance, L_1, when using the formula $\lambda = 1\,887\sqrt{[C_a(L_a + L_1)]}$. The figures quoted in the paper are the values of C_a, L_a, for the two aerials as defined above, and the figure of 994 μH in the advance copies of the paper was a typographical error for 394 μH, as pointed out by Prof. Catterson-Smith, and has been corrected in the *Journal*. The measurement of the aerial resistance was carried out by means of a specially designed measuring-set which did not utilize the aerial tuning inductance. Multiple-feeder aerials were considered before the final design of the Rugby aerial was adopted. The aerial efficiency is of the order quoted by Prof. Catterson-Smith, and I think that he will find that this does not compare unfavourably with the efficiency of multi-tuned aerials at wave-lengths of the order of the high wave-length quoted by him and used at Rugby.

South Midland Centre, at Birmingham, 28 April, 1926.

Mr. G. Rogers: The author remarked that the ether is becoming overcrowded, with the result that interference takes place between the many high-power stations now working. I do not really think that he means this. It may seem to be so with our present knowledge of the ether, and the means of tuning-in to different wave-lengths. It is inconceivable, however, that the saturation point has been even nearly reached. As the ether is apparently illimitable and pervades all space, its capacity to transmit energy may also prove illimitable. In fact, I venture to suggest that means will be found later to obviate any interference. Also it is quite within the range of possibilities that, in the future, many hundreds of thousands of kilowatts of power will be transmitted through the ether without the saturation point being reached. Was any provision made to protect the huge steel masts and the aerial from lightning? One is familiar with the enormous destructive forces that can be liberated and as, apparently, no protection whatever from lightning has been provided, there would seem to be a possibility that the porcelain base and the granite block at the bottom of each of the insulated masts might be fractured if directly struck by lightning.

Dr. C. C. Garrard: With reference to the question of suppressing the generator fields as quickly as possible, I should like to know whether the author has considered the use of a "suicide" arrangement, as used, for example, on rolling mills, with Ward-Leonard control, to kill the generator field instantaneously. In this connection did the Post Office consider the use of a transverter or the mercury-arc rectifier instead of the high-tension

d.c. machines? The use of the oil circuit-breaker for rupturing the high-tension direct current is interesting, and I should like to know whether it is found necessary periodically to change the oil in this breaker, as I have always understood that direct current carbonizes the oil to a greater extent than does alternating current. What was the diameter of wire used for the aerial? This is of interest from the point of view of corona loss. American whitewood seems to be a very useful kind of timber; has the author had any experience of this for making liquid rheostats? When made of ordinary wood these often suffer from burning due to leakage of current through the wood. It seems to me that American whitewood might be used here. The rise of current on the high-speed breaker seems to be exceptionally large. The normal current is 85 amperes; this rises to 1 400 amperes, which is nearly 17 times full load. High-speed breakers are often used in connection with automatic substations, especially with rotary converters, and the rise of current under these conditions when using high-speed breakers is not nearly so large. What was the time taken for one commutator segment to pass from one brush to the next? I wish to compare this with the time given for the operation of the high-speed breaker, viz. 0·02 sec.

Mr. J. A. Cooper: Why do the Post Office engineers use distilled water for cooling their valves, and why is this cooling water itself cooled by a second water system? Since water is such a bad conductor of heat it would appear that some method of cooling such as spraying would be more efficient, but there is, no doubt, a good reason for the system chosen. The author mentioned, in connection with the valve panels, that if one of the five is not available as a spare when one valve breaks down, it is very easy to locate the faulty valve and replace it. I should like to know what means are adopted for rapidly locating faulty valves. Why is alternating current used for the valve filaments? One might have expected the use of d.c. machines for filament heating as well as for the high-tension supply. One of the amplifying valve units referred to in the paper consisted of a valve having an output of 5 kW; I gather that this valve is not water-cooled. I should like to know why a water-cooled valve was not used; they are generally admitted to be very reliable and should have a long life. One lantern slide showed a very large smoothing condenser. Did the Post Office engineers consider the use of electrolytic condensers in any circuit, and, if so, why did they decide not to use them? In connection with the steel mast stays, it would be interesting to know how the strands are made off to the thimbles. This was not apparent from the lantern slide shown. In connection with the type of aerial shown, I should like to know whether any experiments have been made to discover whether there is any high-frequency loss in the steel wire in the centre of the spreaders and whether, after having had experience of this type of aerial, the Post Office engineers still recommend it as the best type of transmitting aerial.

Mr. T. Plummer: I should be glad of some information in regard to the speed of telegraph signals, and to what extent, if any, distance of reception had an effect on the speed of transmission. In other words, was there any tendency for dots and dashes to run into one another at long distances at high speed? The paper deals entirely with the transmission of signals, and it would be useful to have some information concerning the arrangements of circuits and apparatus which were found to give the best results at the receiving end. Are any weakening effects noticeable due to surface leakage on the various insulators, etc., in wet weather, or is it necessary to compensate for this by an increase of power in the aerial?

Mr. E. H. Shaughnessy (*in reply*): In reply to Mr. Rogers it is not the capacity of the ether for carrying energy that is involved, but congestion is due to the fact that the number of frequencies suitable for long-distance long-wave communications and already utilized is very near to the comparatively limited number available. With regard to lightning, the masts act as lightning conductors and are provided with spark-gaps across the base insulation. The aerial is permanently earthed through the aerial tuning inductance.

With reference to Dr. Garrard's remarks, we have not considered the "suicide" arrangement as the present arrangement is very satisfactory. When it is understood that the short-circuit is straight across the machines the rise of current is not abnormal—with rotary converters in automatic substations any short-circuit usually occurs outside the station. The speed of the machine is 750 r.p.m. and the time taken for a commutator segment to pass from one brush to the next brush is 0·04 second. The chief advantage of whitewood is the low energy loss when placed in a high-frequency electric field—we have no experience with it for making liquid rheostats. The oil in the high-tension d.c. oil switch does carbonize after a number of short-circuits and has to be cleaned, but little or no inconvenience results from this at Rugby.

In reply to Mr. Cooper, distilled water prevents the formation of a deposit on the anodes, and with 54 valves in parallel it offers a higher leakage resistance. Spraying involves a large loss of water due to evaporation. The anode trip-gear and indicating devices are shown in Figs. 13 and 14 and described in the paper, from which it will be seen that the overload relay attached to an individual faulty valve provides a visual indication and trips the control circuit, the tripping of the latter actuating an indicator on the panel containing the faulty valves. The use of alternating current for valve-heating is a more convenient and suitable arrangement where a large number of valves arranged in panels are used. The 5-kW glass valve unit is much cheaper than, and quite as reliable as, a water-cooled valve. Electrolytic condensers were considered, but no commercial type suitable for high-voltage use was available. So far as we have been able to determine, the steel rope does not involve loss; and our experience with this type of aerial shows it to be eminently satisfactory.

Mr. Plummer may take it that distance has no effect upon the shape of the transmitted signal; the prolongation and retardation commonly associated with long land lines are entirely absent. Wet weather has no perceptible effect upon the power required to give the required aerial current.

DISCUSSION ON
"ELECTRICITY SUPPLY TARIFFS." *

SCOTTISH CENTRE, AT EDINBURGH, 12 JANUARY, 1926.

Prof. F. G. Baily: The problem of the scientific tariff has troubled supply engineers ever since Dr. John Hopkinson pointed out that the problem existed, and we are as far from an agreed tariff to-day as at any time in the past 30 years. The difficulty lies in the fact that the true tariff should depend on the additional cost in generating station and network of delivering at each moment an additional load. As this has only a remote relationship to the demand of any one consumer, there is small chance of any practicable tariff accurately assessing the proper charge for his meter reading. At the best one can suppose a range of average consumers and assess each class, however varied the real people are in any one class. The whole lesson to be derived from a scientific analysis of total costs, however, reduces to the simple requirement of increasing the total load, the load per square mile of supply area, the load factor, and the uniformity of the load curve. The question shifts therefore to the consumer, for all these quantities depend solely on the consumer, and the best tariff is one which induces him to use electricity so as to bring about the above results. It is a matter of psychology rather than of science. At the same time, papers such as the present one are beneficial in showing which parts of the total cost are most in need of reduction, and what modification of the tariff will be helpful in this way. It points out that the network is the least satisfactory part, and the cure lies in load density and load factor—more consumers per square mile and each using electric current for more purposes, with special attention to night time and summer. A low tariff for summer may induce the use of electric fires and electric cooking among people who argue that they want coal fires in winter and may as well cook and heat water by them. There is insufficient appreciation of the advantage of subsidising new applications. The suppliers will lay down a network in a new area, and offer current at a price which initially does not pay them, and in the same way every extension into a new use for electricity requires similar support. The consumer is naturally reluctant to make experiments at his own expense, and a change in domestic life is one which people are very cautious in adopting. The tariff becomes, therefore, a means of coaxing prospective consumers, with the sole additional feature that its gross amount shall produce the necessary income for the undertaking. Possibly the variety in tariffs is due to different views as to the psychology of the consumer, and this may vary in different localities.

Mr. F. H. Whysall: There is very good reason for bringing up the question of tariffs and considering what form they should take, for, as Prof. Baily says, it is a constantly varying problem owing to the new loads we are acquiring and the altering shape of our load curves. The author raised a point with regard to the relative values of loads and their effect on load factor. He attributed good load factor to a very large percentage of traction load. Some factories, like sugar refineries and works which are taking current over a 24-hour day, have a much more beneficial effect on load factor than the traction load. The analysis of distribution costs really is the important note in the paper, and I thoroughly agree with him that if supply engineers will turn attention to the analysis of distribution costs, in the same way that they have given their attention to the generating costs in power stations, we are bound to make some very substantial progress in understanding what charges should be made for any particular class of business. If one wishes to do anything with the greatest possible accuracy, one must be able to see very clearly what the circumstances are. There is no doubt that the ideal tariff is such as the author has indicated, and he expresses a preference for the two-part tariff which ensures that the undertaking gets paid for standing charges with a small profit, together with a profit on the running charges. The general impression obtained from reading the paper is that we must be doing business at a loss with the charges that we know to be in force. The danger in trying to analyse costs to arrive at the proper charge for any particular service is that they are invariably misleading, and my experience is that they are misleading in always indicating a charge much higher than would be necessary. As illustrating that point, some time ago the manager of a large company told me that he had carried out an extensive investigation into the costs of supplying individual consumers, and he found that a very substantial loss was made on every one of them, and it was very difficult to explain how the company made its profit. If the author can help us to analyse our costs in some way that will give us a reliable indication of what our charges ought to be, instead of being invariably very much higher than they will have to be to get the business, he will be doing a very great service.

Mr. A. Mears: The author has developed an aspect of the costs to supply electric energy which has probably been overlooked in the past to a large extent, and he shows how distribution costs are affected by the "form factor" of the load on a particular main or set of mains. Unfortunately it is not possible for a supply undertaking to refuse to supply consumers because of the particular manner in which the load is taken—omitting of course very exceptional cases—and the bad have to be taken with the good. From this it follows that the bad effect of some types of consumers must be counterbalanced by inducing good types of consumers to take a supply, and this is best attained by offering an attractive tariff. Diversity of types of consumers with suitable proportions of each type

* Paper by Mr. H. M. Sayers (see vol. 63, p. 850).

should be the aim of every undertaking, and if this is attained I think that the difficulty with the undue costs of distribution owing to form factor will disappear. In Edinburgh we have a good power load with very diverse types of consumers, and a lighting load which is well divided between business and domestic consumers. The domestic heating load is increasing and, in addition, we have a good tramway load. The author refers to places where the units sold to consumers are only about 55–60 per cent of the units at the station bus-bars, but this is surely very exceptional. It is also stated that distribution charges are 2 to 4 times the cost of generation, and I presume from this that the interest and sinking fund together with working expense are included under each heading, and, in addition, the value of the units lost in distribution. In Edinburgh this figure is about one half instead of double. There must be some very exceptional conditions prevailing where the distribution costs are so high, and the question of devising a suitable tariff to remedy this state of matters would be most urgent. The author considers that the principle of charging on what the service will bear cannot be followed very far, but this is probably more idealistic than what usually obtains in practice. A high lighting rate is very frequently charged so as to foster increased consumption at the heating rate with many domestic tariffs. Again, it is the exception to charge meter rentals. The author points out that a rental to cover meter and service charges is equitable and in this I agree, but in practice it is very advisable to avoid it. The business aspects of selling electricity and how a tariff appeals to the ordinary consumer, must also be kept in view. In this connection it is very advisable to have a simple tariff, and probably the method of grouping consumers and charging each group at different rates is the most practical. Too many groups are not to be desired, and I do not think that domestic consumers can very well be divided. In connection with group charging, allowance is made for the diversity factor obtaining in the group itself, and also the relation of the group peak to the principal peak of the station. A study of the general tariffs in use indicates that the grouping of consumers and charging according to their group is very prevalent. The author recommends the grouping method and shows by an example how ice and refrigerating companies can be debited with a small proportion of the kilowatt charges owing to the nature of their load, but we find it better to arrange these consumers on a flat rate, and they keep off the peak during the winter months. The domestic load is now being exploited as representing a new type of load with a different character from other loads, and consequently improving the general demand factor and load factor. Load factor is obviously of the utmost importance and, taking conditions as they are, the best way of improving it is to develop the most diverse types of loads in suitable proportions.

Mr. C. W. Marshall: I do not consider that the author's domestic tariff is at all practicable. I believe that the key-note of the situation lies in simplicity, and I would remind him that the use of Kelvin's law in the old days, led to the erection of power stations on the top of a hill in the middle of the town. My view is that supply undertakings should demand a fixed service charge and a flat rate now; that will be the best thing possible for improving the load factor. It can bring about, too, the further simplification that the meter can be calibrated in money—in shillings if required—and the apparatus can be rated in pence or shillings per hour. On the psychological aspect of analysis I cannot agree with the author at all.

Mr. E. Seddon: The author has approached the subject of tariffs from a new viewpoint, and his observations on the cost of the distribution system as affecting the selling prices are interesting from a scientific point of view. We must, however, have regard to public opinion in these matters. We are a comparatively young industry, and in order to compete with other forms of light, heat and power we must make our commodity popular and attractive in price, and any tendency to multiplicity in tariffs can only have the effect of retarding the progress we desire. It is quite safe to say that no supply engineer would dare to make a statement that his tariffs provide for an equal percentage of profit from all consumers. It is the old tale of making up on the swings what is lost on the roundabouts. Given an equal load factor from two consumers, one near the generating station, the other on the fringe of the system, it is obviously unjust to make the same rates of charge to both consumers, but if a truly scientific basis of cost were taken the price would vary from house to house. I am convinced that it would be intolerable to charge varying flat rates in the same area of supply, and I submit that a common form of tariff must be applied whatever the distribution costs amount to. This principle is accepted in the postal and other services. In my opinion the method of fixing the standing charge of a two-part tariff on the assessment or floor area of property is wrong in principle, and such methods of charge only expose our inability to frame suitable rates based on the cost of providing a supply of electricity. The chaos in tariffs creates suspicion in the minds of potential consumers, and each one imagines that by negotiation he can get an advantage over his fellows. I am glad to know that the question of tariffs is being taken up seriously on a national basis, and I hope that a universal system of charge will follow as a result of these investigations. Load factors of individual consumers are apt to be misleading, as it is quite possible for a lower load factor to be more economical than a higher load factor, depending on the period of maximum load. Diversity is, I think, the more important factor, but I do not think we need trouble ourselves too much about these matters, as I am convinced that the load factor at the generating stations will improve automatically with the general application of electricity for all purposes. We in Edinburgh have been criticized in some quarters for selling current for lighting at too low a rate, namely $3\frac{3}{4}$d. per unit with discounts, but I submit that such criticism is only fair if these rates were made at the expense of other users. In consequence of the fact that our domestic heating rate is practically $\frac{3}{4}$d., and that low-tension power supply varies from $1\frac{1}{2}$d. to $\frac{3}{4}$d., I do not think

that anyone can justly state that we are showing undue preference to the lighting consumers. In addition to our flat rates, we have followed the lead of Glasgow in adopting the combined-rate method of charge to allow of a small amount of heating and power being connected to the lighting circuits.

Mr. W. K. Fleming (*communicated*): The subject of electricity supply tariffs seems to be a perennial one, yet it is well to pause periodically to renew our efforts to elucidate the ideal tariff, by the presentation and discussion of a paper such as the present one. The ideal tariff is one that (*a*) ensures to the supply undertaking a fixed sum per annum (plus a reasonable profit) in respect of the standing charges incurred in supplying the consumer, with all units used charged at running cost (plus a reasonable profit); (*b*) reduces the average price per unit as the load factor and diversity factor increase; (*c*) requires only one meter; and (*d*) is easily understood by the consumer and appeals to his sense of equity. The analytical examination of the subject made by the author is extremely valuable, especially the Section dealing with distribution economy. The domestic load is progressing rapidly just now and it is certain that the next few years will witness a tremendous development. The problem of distribution design will be one of great import, for who can foretell with any degree of accuracy to what extent and at what rate the demand from the vast domestic field will grow? The tariff put forward by the author covers, in the main, the conditions stated for the ideal tariff, although the law of averages is used in so far that the basis of calculation is for classes of consumers and not individual consumers. One might expect in connection with the suggested new tariff that some addition to the accountancy and clerical work would be experienced in view of fairly frequent changes of consumers from one class to another. The question of whether the rate should be levied as a flat rate or as a periodic fixed charge with a low running charge is one that will be influenced by local conditions. In general, large consumers do not mind a high fixed charge, but for small consumers who have many other fixed periodic payments to meet, the fixed charge must be reasonable, otherwise the flat rate is preferable. One benefit of the flat rate is that prepayment meters may be used. This method of payment, using 1d. and 1s. slot meters, has been very successful in Greenock, where it has been in operation for 5 years. Reference is made in the paper to the fact that the lighting load will probably cease to be a predominant feature of the peak load as the use of electricity for other purposes increases. Whilst it is true that the influence of the lighting load is not now so great in districts where the heating and cooking load has been intensively cultivated, yet it is well to keep in mind that in the future it is to be expected that the lighting load in the home will also increase. Most engineers will be aware of the general campaign in favour of "more and better light" which has been proceeding with the co-operation of the Electric Lamp Manufacturers' Association of Great Britain. During the present winter, attention has been concentrated on shop-window and shop interior lighting. Due to the active educative propaganda which has been carried on, we have experienced in Greenock during the past months a very large increase in the shop-lighting load, the intensities of illumination in many cases being doubled. Even now, higher standards of illumination in the home are being advocated, and it is to be expected that when the subject is tackled thoroughly and systematically in the same way as shop lighting, the lighting load will reassert itself to some extent at the time of peak load. The author states that for the immediate future it may be advisable to limit the maximum lighting demand of domestic consumers under the tariff he proposes. However desirable this may be from the supply undertaking's point of view, it is a mistake in policy to restrict the user. The consumer should be at liberty to use the electric service as it suits him to do so. It is permissible, of course, to restrict the hours of use for an electrical hot-water storage tank, for then the commodity that the consumer wants to use—the hot water—is available at any time of the day.

Mr. H. M. Sayers (*in reply*): Prof. Baily is quite right in laying stress on the relation between tariffs and the psychology of the consumer. That is why I advocate classified flat rates as the simplest to understand and apply. The consumer in one of the higher-rated classes may grumble at being charged, say, 3d., whilst a neighbour is charged 1½d. per unit, but the answer is that if he uses the same proportion of lighting, heating and cooking, he will get the same rate; and this should show him that the difference is not arbitrary, but is an endeavour to be fair.

Mr. Whysall says that the analysis of costs for any particular service always indicates a much higher charge than is proved to be necessary. This experience suggests that insufficient credit is given for the diversity effects. I did not attribute the high load factor of certain stations to their traction load, but mentioned that all the stations with published load factors of 30 per cent and over have traction loads. The traction (tramway) load is an instructive example of the value of diversity. Though a tramway load by itself may show a load factor of only 20 to 25 per cent, yet it fits in with other loads in a highly beneficial way. In an industrial town the tramway peaks occur in moving workers to and from their work just before and just after the factory and office loads come on and go off, including the midday break in many cases, and on Saturday afternoons when there is no factory load. Load diagrams and log sheets of Mr. Whysall's own system, which I have examined, show this effect clearly. The few works which run 24 hours per day have by themselves a very high load factor. They require for their supply the full-load amount of plant, plus spares; whilst a tramway load does not add to the plant requirements up to its peak loads.

Mr. Mears generally agrees with the paper. The cases mentioned of very high losses between units generated and units sold are where original local direct-current stations have been displaced by more distant three-phase stations, with direct-current distribution retained through converting plant. These cases will disappear in time. A remunerative tariff must include the charges for services and meters, as well as the kilowatt

charges; for domestic consumers it is better to consolidate these into flat rates than to make specific charges. The statement that the distribution costs in Edinburgh are only about half the generating costs, shows that the Edinburgh system must be unusually compact and unusually well-designed for its present load. It seems to justify the low rate for lighting mentioned by Mr. Seddon.

I agree with Mr. Marshall that simplicity should be the keynote of tariffs, and I hoped that I had shown one way of achieving it; what can be simpler than a flat rate? I cannot conceive how the use of Kelvin's law led to the erection of stations in unsuitable places.

Mr. Seddon's appreciation of the value of diversity is welcome. The paper advocates methods which will encourage and recognize diversity. If they do that, the rates will be automatically reduced to a small number as domestic electrification becomes general and the proportions of lighting, cooking, heating, etc., become sensibly uniform.

I rather agree with Mr. Fleming's criticism of the suggestion that the maximum lighting demand might be restricted for the immediate future. It was mentioned as a concession to the evident fears of some supply undertakings that a low flat rate may produce an expensive domestic lighting peak. I do not share those fears, and I believe that any such condition would soon prove unnecessary and fall into disuse. All the published statements of load and consumption where heating and cooking services are given support this view.

It is gratifying to find that the subject of distribution-costs as affected by load diversity and form factors was appreciated in the discussion. I would reiterate the suggestions in the paper that a much more general use of measurements on the distribution systems should be adopted. The very complete system of measurements used in modern power stations is amply justified by the economies effected and maintained. Similar results may be expected by similar methods applied to the distribution plant. It is only by the knowledge derived from measurement that efficiency can be raised and maintained.

INSTITUTION NOTES.

Summer Meeting.

On account of the strike and in view of the coal situation, the Summer Meeting at the North-Eastern Centre which was to have been held this month has been postponed to next year (14th–17th June, 1927).

Council's Nominations for Election to the Council.

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-President, Honorary Treasurer, and Ordinary Members of Council on the 30th September, 1926:—

President. (*One Vacancy.*)

W. H. Eccles, D.Sc., F.R.S.

Vice-President. (*One Vacancy.*)

Colonel T. F. Purves, O.B.E.

Honorary Treasurer. (*One Vacancy.*)

Lieut.-Col. F. A. Cortez Leigh, T.D., R.E.

Ordinary Members of Council.

Members. (*Four Vacancies.*)

A. C. Cramb.
A. H. Railing, D.Eng.
Prof. S. Parker Smith, D.Sc.
A. J. Stubbs.

Associate Member. (*One Vacancy.*)

F. W. Crawter.

Premiums.

The following Premiums for papers have been awarded by the Council:—

The Institution Premium (*value* £25).
L. C. Grant. "Developments in High-Power Fusible Cut-Outs."

The Ayrton Premium (*value* £10).
S. Mavor. "The Applications of Machinery at the Coal Face."

The Fahie Premium (*value* £10).
B. S. Cohen, A. J. Aldridge and W. West, B.A. "The Frequency Characteristics of Telephone Systems and Audio-Frequency Apparatus, and their Measurement."

The John Hopkinson Premium (*value* £10).
S. Ferguson. "A General Survey of the High-Tension Switchgear Field."

The Kelvin Premium (*value* £10).
P. Dunsheath, O.B.E., M.A., B.Sc. "Dielectric Problems in High-Voltage Cables."

The Paris Premium (*value* £10).
T. Carter. "The Engineer: his Due and his Duty in Life."

A Premium (*value* £10).
Prof. S. P. Smith, D.Sc. An All-Electric House."

A Premium (*value* £10).

J. L. THOMPSON, M.Sc., and H. WALMSLEY. "Notes on the Testing of Static Transformers."

A Premium (*value* £5).

A. B. WOOD, D.Sc. "The Cathode-Ray Oscillograph."

WIRELESS SECTION PREMIUMS.

A Premium (*value* £10).

R. A. WATSON WATT. "The Directional Recording of Atmospherics."

R. A. WATSON WATT and J. F. HERD. "An Instantaneous Direct-reading Radiogoniometer."

A Premium (*value* £10).

J. HOLLINGWORTH. "The Propagation of Electric Waves."

A Premium (*value* £10).

R. L. SMITH-ROSE, Ph.D., M.Sc., and R. H. BARFIELD, M.Sc. "The Cause and Elimination of Night Errors in Radio Direction-Finding."

The Premiums for papers read before the Students' Sections will be announced later.

Informal Meetings.

77TH INFORMAL MEETING (8TH FEBRUARY, 1926).

Chairman : Mr. G. R. Polgreen.

Subject of Discussion : "Modern Applications of Ball and Roller Bearings" (introduced by Mr. R. J. Mitchell).

Speakers : Messrs. C. H. Smith, W. E. Rogers, A. F. Harmer, H. Brazil, C. Belcher, W. A. Erlebach, W. L. Wreford, C. R. Garrard, C. S. Clarke.

78TH INFORMAL MEETING (22ND FEBRUARY, 1926).

Chairman : Mr. H. T. Young.

Subject of Discussion : "Some Changing Characteristics in the Application of Electricity to Public Supply" (introduced by Mr. A. F. Harmer).

Speakers : Messrs. A. Wright, W. E. Rogers, P. Dunsheath, O.B.E., W. A. Erlebach, S. V. Hook, W. Lunn, M. D. Hart, M.Sc., R. Grierson, H. T. Young.

79TH INFORMAL MEETING (8TH MARCH, 1926).

Chairman : Mr. M. Whitgift.

Subject of Discussion : "A Recent Development in A.C. Apparatus" (introduced by Mr. F. Creedy).

Speakers : Messrs. A. F. Harmer, J. Eck, J. Coxon, M. D. Hart, M.Sc., W. E. Rogers, A. J. Gill, R. J. Mitchell, A. H. E. Tomkinson, A. G. Hilling, J. F. Shipley, C. G. King, J. R. Bedford, J. H. St. H. Mawdsley, F. Pooley, A. H. Allen, W. L. Wreford, W. S. Gearing.

80TH INFORMAL MEETING (22ND MARCH, 1926).

Chairman : Mr. A. H. Allen.

Subject of Discussion : "The Performance of Mercury Arc Rectifiers" (introduced by Mr. G. Rogers).

Speakers : Messrs. A. F. Harmer, S. C. Bartholomew, M. D. Hart, M.Sc., W. E. Rogers, F. Creedy, K. H. Tuson, W. Lang, A. Honeysett, G. H. Fowler, R. Grierson, J. Coxon, A. G. Hilling, J. C. Read, J. F. Perrin, J. R. Bedford, J. F. Shipley, W. W. Hughes, W. S. Hunt, R. V. Hook, A. H. Allen.

81ST INFORMAL MEETING (12TH APRIL, 1926).

Chairman : Mr. J. Coxon.

Subject of Discussion : "The Linking Together of Wireless and Wire Communication Systems" (introduced by Captain P. P. Eckersley).

Speakers : Messrs. J. F. Shipley, N. Ashbridge, H. L. Kirk, W. A. Erlebach, R. Sandeman, E. J. Buckingham, A. C. Brown, E. S. Ritter, W. Day, A. Rosen, Ph.D., G. F. Findley, J. Coxon.

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The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 April–25 May, 1926:—

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THE SEVENTEENTH KELVIN LECTURE.

"THE MECHANICS OF THE ELECTRIC FIELD."

By Sir J. J. Thomson, O.M., M.A., F.R.S., Honorary Member.

(*Lecture delivered before* The Institution, 22*nd April*, 1926.)

The subject which I have selected for the Kelvin Lecture is one that from the very beginning of his scientific career was never long absent from Lord Kelvin's thoughts. It is one, too, which researches only dawning towards the close of his life have put into quite a new aspect. These researches have given us very definite information as to the structure of the atom, they have taught us that the atom is made up of electrons and positively electrified particles of known masses, they have told us the number of electrons and positive particles present in each atom; they have, in fact, given us a definite specification of the electrical state of the atom. With this in our possession it would seem as if we ought to be able to deduce the properties of the atom, by calculating by means of the laws of electromagnetism the behaviour of this definite electrical system. We find, however, if we do this, that the properties of our mathematical atom are in some respects in contradiction to those of the real atom. It is of course a gigantic extrapolation to pass from any system which we can test by direct experiment, and for which the laws of electromagnetism have been verified, to systems like the atoms, where the times and distances involved are of an entirely different order of magnitude. The extrapolation fails, but the point is that if the usual interpretation of these laws is the right one it ought not to fail. The equations expressing these laws are:

$$\frac{dF}{dt} = c \text{ (curl H)}$$

$$\frac{dH}{dt} = c \text{ (curl F)}$$

where F and H represent the electric and magnetic forces respectively and c is the velocity of light. The only constant which these equations involve is the velocity of light, and extrapolation to any scale of time or space should be valid unless it introduced velocities comparable with those of light.

I propose to discuss the question whether the equations of classical electrodynamics or, for the matter of that, classical dynamics are as fundamental as they have been thought to be; whether, instead of giving us a complete representation of the field of force, they do no more than give us the relations between the average value of the quantities used to define the field. That, in fact, they express statistical and not particle dynamics.

Let me introduce the subject by considering the oldest of the laws of electrical action, Coulomb's law, which states that two oppositely electrified bodies attract each other with a force varying inversely as the square of the distance between them. The interpretation assigned to this law is that if A represents one of these bodies and B the other, then A receives a stream of momentum in the direction A B, while B receives a stream in the direction B A, and that in any small time δt the amount of momentum received by either A or B is equal to $\delta t \,.\, Ee/\mathrm{AB}^2$, where E and e are the electrical charges on A and B respectively. The process by which the momentum is communicated has, I think, always been regarded as a perfectly continuous one: that, however acute our powers of detecting variations in momentum might be, we should never be able to detect any break in the continuity of the supply of momentum, and, moreover, that at each instant the gain of momentum of A would be simultaneous with the loss of the same amount of momentum by B, and also that the rate of communication of momentum is determined without any ambiguity whatever when the positions of A and B are known. We have no direct experimental proof of the continuity in the supply of momentum, for all our experiments are on effects which extend over a finite time, a time which is very long indeed compared, for example, with the time which would be taken by an electron to describe an orbit round a positive charge in the atom. All that direct experiment can teach us is that eE/AB^2 is the average rate at which the momentum is communicated, the average being taken over a time which is very large compared with the times occurring in atomic dynamics. Direct experiment gives us no information as to whether the momentum was supplied in an uninterrupted flow, or whether it was given by a series of separate impulses separated by finite times. Yet the difference is a vital one, for it is only on the first of these suppositions that we are justified in applying the methods and principles of classical dynamics to discuss the dynamics of the atom. I may illustrate my point by a simple case. The engineer treats the pressure of gas on a piston as a perfectly continuous force and gets quite accurate results. Yet we know that this pressure arises from the impacts of the molecules of the gas against the piston, that it resembles a series of blows with a hammer rather than a continuous force. These blows, however, succeed each other so quickly that in ordinary cases we cannot separate the effect of one blow from that of another; all that observation of the piston could tell us is the average amount of momentum communicated to it, taken over a time which is very long compared with the interval between two blows. By merely observing this average we cannot determine whether the blows

succeed each other at regular intervals, or whether they follow each other at intervals occurring quite at random; whether they are very small blows following each other at very small intervals, or larger blows following each other at longer intervals. Let us suppose, however, that we reduce the pressure of the gas; this will lengthen the interval between the collisions, and we may imagine the pressure reduced to such an extent that the interval between the collisions becomes long enough for us to be able to follow in our experiments the effect of each collision. At this stage the effect produced by the gas on the piston cannot even approximately be represented by a constant force. The amount of momentum received by the piston in one of these short intervals will be a matter of chance. We cannot say that in a certain time a definite amount of momentum will be communicated to the piston; all we can say is that in this time t the probability that the piston receives n blows is

$$\left(\frac{t}{T}\right)^n \frac{1}{n!} e^{-\frac{t}{T}}$$

where T is the average interval between the blows. We see that in this stage the results and methods are quite different from those obtaining when our experiments extended over a time long enough to include an immense number of collisions; in the latter case the motion of the piston can be determined without ambiguity by classical dynamics and, given the initial conditions, there is only one solution. In the other case the motion of the piston may be almost anything within certain limits; it is determined far more by the theory of probability than by dynamics. The fact is that we have to deal here with two interacting systems, the piston and the molecules of the gas, and the distribution of the molecules is not fixed by the position and motion of the piston, but has to be determined by the theory of probability. Thus, even for the same position and velocity of the piston, we may have different distributions of molecules; the behaviour of the piston will depend upon the kind of distribution, unless the number of molecules is so large that the distributions which differ from a standard one are insignificant in number compared with those which approximate to it.

It may be urged that though we cannot prove the classical hypothesis of a continuous flow of momentum by direct experiment, and though it apparently leads to results which are not in accordance with the electrical theory of the atom, yet this conception is so much simpler and seems so much more probable than the idea of intermittence that we ought to retain it and seek for some other explanation of the discrepancies to which it seems to lead. Is, however, the idea of a continuous flow of momentum so much simpler and more probable than that of intermittence? No doubt the mathematical analysis is simpler for the continuous than for the intermittent flow, but is the idea simpler from the physical and mechanical point of view? Suppose our senses were so acute that we were able to see the molecules of a gas and watch their effects upon each other, or, to put it another way—Maxwell, as you know, introduced the idea of a molecule endowed with intelligence, and showed that it could upset the second law of thermodynamics. Now let us suppose that Maxwell's "demon" was a mathematician, and that he set to work to develop a system of dynamics. Would not to him the idea of a continuous flow of momentum seem remote and far removed from reality? What he sees going on around him is one big bang after another, and not the halcyon repose of continuous smooth motion without any jerks or breaks. Would it not be more natural for this molecular Newton to take as his fundamental idea not a uniform flow of momentum but collisions which succeeded each other irregularly, the average interval between the two collisions depending on the pressure of the gas.

I want to bring before you some of the consequences of supposing that the electric force is of this nature, that it consists of separate impulses separated by finite times. I must point out that this conception involves the existence in the universe of a structure beyond that represented by electrons and positive particles; if there were no structure of this kind, we could not account for the intervals which elapse between the impulses. This structure must be far finer in texture than the electrons; thus, on this view, the electron does not represent the last word in minuteness and there are still smaller entities awaiting discovery by the physicists. For heuristic purposes, i.e. for the purpose of making our meaning clear, and without committing ourselves to the reality of this particular structure, we may liken it to a sub-atomic and sub-electronic gas, the particles of which are much finer than the electrons. It is in these particles that the energy and momentum of the electric field are stored. We may regard these particles as concentrated round the electric charges, each charge carrying with it an atmosphere of these particles. The particles are crowded together near the centre of the charge, but get more and more widely separated as the distance from the centre increases. To distinguish between the positive and negative charges, we may suppose that the particles rotate round the charges and that the rotation as viewed from the centre of the charge is in one direction for the positive and in the opposite direction for the negative charge.

The particles bombard intermittently the charges round which they are congregated. If there were only one charge in the field the particles would be symmetrically distributed around it and the bombardment would not, on the average, make it move in one direction rather than in another; but when two or more charges are near together the symmetry of the distribution of the particles is disturbed and the bombardment results in the charges acquiring momentum. Let us now consider in some detail the way in which the effects produced by intermittent forces differ from those due to continuous ones. We may represent the intermittent force analytically by saying that the chance of a body on which this force is acting receiving in time δt an increment of momentum is $\delta t/T$, where T is the average time between two increments and is a measure of the fineness of the time structure of the electric field. Let I be the increment of momentum given at each impact; then the expectation of the increase in momentum in time δt is $(I/T)\delta t$. If the

force had been continuous and equal to F, the increase in momentum would have been equal to $F\delta t$ and have had a definite value. On the intermittent view, instead of a certainty we have an expectation, sometimes the results will exceed expectations, sometimes they will fall below them; but on the average, when there are a great many increments, i.e. when δt is large compared with T, they will differ but little from the expectation, so that the increase of momentum will be $(I/T)\delta t$, or the same as the body would receive from a continuous force $F = I/T$. Thus for effects lasting for times long compared with T, the results will be very nearly the same whether the forces are continuous or discontinuous; but for shorter times they will be very different.

For if the chance of an increment is $\delta t/T$, then we can easily show that the chances of certain events happening in the time t are as follows:—

(1) The chance that the body receives no increment at all is $e^{-t/T}$

(2) The chance that it receives one increment and no more is $\frac{t}{T}e^{-t/T}$

(3) The chance that it receives two increments and no more is $\frac{1}{2}\cdot\frac{t^2}{T^2}e^{-t/T}$

(4) The chance that it receives r increments and no more is $\frac{1}{r!}\cdot\frac{t^r}{T^r}e^{-t/T}$

The ratio of the chance that there should be $(r+1)$ increments to the chance that there should be r increments is thus $\frac{1}{r+1}\cdot\frac{t}{T}$

Thus until $(r+1)$ is greater than t/T the chance of a larger number of collisions is greater than that of a smaller one; but when $(r+1)$ is greater than t/T the chances of a larger number rapidly diminish. The number of collisions for which the chance is greatest is t/T; the expectation of increase in momentum is It/T, or Ft if $F = I/T$. Thus on the discontinuous theory the most probable increase in momentum is the increase which would occur on the continuous theory. On the discontinuous theory, however, there is a finite probability that the increase should be either greater or less than this value.

We may illustrate the difference between a continuous and an intermittent force by considering a simple case. Take that of an electron projected horizontally and exposed to the influence of a vertical force for a time t. Whether the force be continuous or intermittent the horizontal velocity will remain constant and the horizontal distance travelled is not affected by the intermittence of the force. When the force is continuous and constant there is only one orbit, the parabola. If the force is intermittent there will be an infinite number of possible orbits. In fact any polygon is a possible orbit, provided the rth side makes an angle with the horizontal such that $\tan\theta_r = kr$, where k is a constant.

Thus a horizontal straight line is a possible orbit, because there is just a chance that the electron may escape a collision for the time t. There is an infinite number of two-sided orbits where the electron makes one collision in the time t. At the end of these orbits all the electrons have the same kinetic energy, but they will not all have suffered the same vertical fall, i.e. they will not all have the same potential energy; this is an illustration that the Conservation of Energy in the ordinary sense does not hold for these intermittent forces. To get the same increase in kinetic energy as they would under the action of a continuous force, some of the electrons under the intermittent force would have lost less, others more, "potential energy" than they would under the continuous force. Again, there is an infinite number of 3-, 4-, 5-sided orbits; there is no limit to the number of sides, and the greater the number of sides the greater the kinetic energy acquired by the electron describing the orbit. All these are possible orbits, but some of them are very improbable. We can calculate the probability of any type of orbit. We have already seen that the most probable number of sides for the orbit is t/T; this makes the final momentum have the same value and direction as it would under the continuous force. But even when the number of sides is given, the individual sides may have very different lengths. We can show that the most probable orbits are those where the impacts are equally spaced over the journey. For divide the space passed over by the orbit into vertical strips, and let the breadth of the first be x_1, that of the second x_2, that of the third x_3 and so on; it is easy to show that the chance that the first collision occurs in the first strip, the second in the second, and so on, is proportional to $x_1 \times x_2 \times x_3 \times x_4$; and, since $x_1 + x_2 + x_3 + x_4 + \ldots$ is constant, this is a maximum when $x_1 = x_2 = x_3 = x_4$, i.e. when the increments of momentum are received at equal intervals. Thus, again, the most probable orbit is the one that approximates most closely to that described under a continuous force. It is, however, only when t/T is a very large number that the chance of orbits departing widely from this becomes inconsiderable.

I have already pointed out that the principle of the conservation of energy in its usual form does not apply when the forces are discontinuous. This is because the energy is stored in the particles which constitute the electric field, and the distribution of these particles and their energy may change, even though the electrons and positive particles do not move; an electron may take energy from these particles or give up energy to them without suffering any change in its potential energy.

Take, for example, the case of an electron starting from an infinite distance from a positive particle, falling close to the particle and then receding from it until it is again at an infinite distance away. The potential energy is the same at the beginning and end, so that if the principle of the conservation of energy holds, the kinetic energy at the end must also be the same as at the beginning. If we suppose that the mass of the positive particle is infinite compared with that of the electron, so that it absorbs no kinetic energy, the velocity of the electron at the end of the journey must be the same as that at the beginning. This need not, however, be the case if the force is discontinuous, for when the electron is falling from aphelion to perihelion the increase in its kinetic energy depends upon the

number of increments of momentum it receives during its journey from aphelion, and when it goes away from perihelion to aphelion its loss of energy depends upon the number of increments of momentum it receives on the return journey. Now, according to the intermittent theory of the force, these numbers are not fixed but are a matter of chance, so that there is a finite probability that the electron on its journey from aphelion to perihelion may receive more than the normal number of increments, whilst on the return journey it would receive less. If this were so, the electron would receive more energy in its approach than it would lose on its return, so that it would have gained by the journey kinetic energy without losing potential. The chance of losing more energy on its return than it gained on the approach is just as great as in the case we have considered, so that some electrons may lose kinetic energy by the journey without gaining potential energy. The fact that it is possible for an electron to gain energy in this way has, I think, an important application to the question of the spontaneous dissociation of atomic systems.

Let us take the case of an electron describing an elongated orbit about a positive centre, and suppose that in going from aphelion to perihelion it receives more than the normal number of increments of momentum; when it gets to perihelion it will have more than the normal amount of kinetic energy. Suppose that the increments in the return journey are not more than normal, then on reaching aphelion again the electron will have more kinetic energy than when it started. If this increase in energy exceeds a certain amount, i.e. if it is so great that when the electron approaches the place from which it started it has sufficient energy to carry it against the attraction of the positive centre from this place to an infinite distance, the electron will break away and separate from the positive centre. Thus in this way the discontinuous character of the force may give rise to a spontaneous dissociation of the system—spontaneous in the sense that it is a consequence of the character of the forces acting between the members of the system, and does not depend upon collisions with other molecules or electrons or on the influence of radiation. The probability of the electron receiving an increment of energy ω by the journey can be shown to vary as $e^{-p\omega^2}$, where p does not depend upon ω. The probability thus diminishes rapidly as ω increases; the probability of acquiring a certain amount of energy is inversely proportional to the average life of the atom, so that this life will increase very rapidly with the amount of work required to dissociate it. An example of this spontaneous dissociation is afforded by the negative ions in gases; these have two phases, one being the electron, the other a complex of the electron and one or more molecules. The first phase is continually passing into the second by the combination of electrons with molecules, and the second into the first by the dissociation of the complex. The rate of this dissociation is independent of the pressure of the gas and there is no evidence that it is affected by radiation. Similar considerations show that when the force is intermittent an electron moving past a positively electrified particle may acquire or lose energy by the collision, even though the mass of the particle is infinitely greater than that of an electron, when, if the force were continuous, there would be no transference of energy to or from the electron. Thus it might be possible for an electron projected with less than the energy required to ionize a gas to acquire by collisions with positive particles enough energy for this purpose.

The dissociation considered is that of an electron describing an elongated orbit, and the argument would not apply to a circular one. Similar results would, however, follow for such orbits if we suppose that a body in a field of electric force receives impulses at right angles to the direction of the electric force as well as along it, but that at right angles to the force there are on the average as many positive as negative impulses. If these impulses are, however, discontinuous, there is a finite chance that the number of positive impulses should differ from that of the negative; in this case the body would gain or lose momentum in a direction at right angles to the electric force. Thus an electron describing a circular orbit would have a finite chance of having its tangential velocity and therefore its energy increased. If this increase in the energy amounted to that required to tear the electron away from the positive charge, the system would dissociate.

Let us now consider more in detail other characteristics due to the intermittence of the electric force: these will naturally occur only when the phenomena involve times short enough to be comparable with the time interval of the electric field. This time interval, we may say in passing, is not constant but varies with the strength of the electric field, diminishing as the strength of the field increases. Now suppose the electric field acts on an element of volume which contains a very large number of systems, be they electrons, atoms, or anything else which can be effected by electric force; and suppose the time t the force acts is small compared with T the time interval of the force. We can easily show that the momentum received by the whole system will be the same as if the force had been continuous and equal to I/T. This will be true whatever the time may be during which the force acts. The distribution of momentum will, however, be very different in the two cases, when the time of action is small compared with T. For when the force is continuous the momentum will be equally distributed among all the members, and each individual will possess a small amount, the same as that of its neighbour. In the case of the intermittent force the vast majority of the systems will not have received any momentum at all, but a few will have received quantities that are enormous compared with those which would have been received if the momentum had been equally divided. When the time t is large compared with T, the distribution of momentum under the intermittent force will approximate very closely to that under the continuous. The energy communicated to the collection of system by the intermittent force can be shown to be greater than that by the continuous one in the proportion of $(T + t)$ to t, so that when the time is small compared with T the system absorbs far more energy from the intermittent field than it would from the continuous field which in the long run is equivalent to it.

The difference between the continuous and the inter-

mittent force is accentuated when the forces are reversed after short intervals. For if the force is continuous and acts for a time t, each of the systems will acquire an amount of energy proportional to $(Ft)^2$. If at the end of this time the force is reversed and acts for an equal time in the opposite direction, the energy will be taken out of these systems and restored to the electric field. If, however, the field is intermittent and t is small compared with T, only a small fraction of the systems will have received any energy. When the field is reversed the chance that any of the few systems previously excited will receive negative momentum and so lose energy is exceedingly small, and the great majority of systems which receive energy in the second interval will not have received any in the first. Thus the systems absorb practically as much energy from the electric field in the second interval as they did in the first; whilst, under the continuous field, instead of absorbing energy, in the second period they gave up all they had got in the first. Thus the intermittence of the field may lead to a great increase in the absorption of energy from alternating fields by systems exposed to the action of the field. The question of the transmission of waves of electric force when the period of the wave is shorter than the time interval of the electric force is therefore one that introduces considerations quite different from those of electrical waves of longer period, and requires special treatment.

In the first place, the equations of the electric field do not, if we take the view of the intermittence of force, represent relations between physical quantities which have an existence at any particular time; they have respect rather to the relations between certain statistical quantities, averages taken over a time which is long compared with the time interval of the electric field; for these equations represent relations between electric and magnetic forces. From the point of view of the intermittent theory, electric and magnetic forces do not represent anything that is happening at any particular instant, but an average taken over a time which is long compared with the time interval of the electric field. Thus these equations are meaningless when the times available are not long enough to allow this average to have a definite value. They would not apply, for example, to the case of electrical waves if the period of the waves were less than the time interval of the electric field. The consideration of what would happen to electrical oscillations whose period is shorter than the time interval of the electric field, is a matter of great interest and importance. The time interval T of the electric force is connected with F the intensity of the force by the relation $F = I/T$, where I is the momentum communicated at each impulse, so that as the intensity of the electric field diminishes I/T diminishes also. Now, whatever view we may take of the origin of the impulses which produce the force, whether, for example, we regard them as due to collisions with a swarm of very minute particles or in any other way, we should expect the interval between the collisions to increase as the field gets weaker. The time interval would be a function of the intensity of the field and would be longer for weak fields than for strong. Now consider an electron oscillating with a definite period T_0. Close to the electrons the electric field may be very intense, and its time interval may be short compared with T_0 the period of the oscillations. In such a region as this the classical theory would apply and electrical waves would travel through it, starting from the source of the oscillations. But as the distance from the source increases, the electrical field gets weaker and the time interval continually increases until when a certain distance is reached the time interval becomes comparable with T_0. When this region is reached it seems clear that the waves must stop, as Maxwell's equations from which the wave motion is deduced do not hold. We have seen too that when T_0, the interval between the reversals of the electric force, is small enough to be comparable with the time interval, the absorption of the energy of the electric field is far greater than when T_0 is long compared with the time interval. We should not therefore expect these waves to travel further away from the source than the place where the time interval of the electric field is equal to the period of the oscillations. For oscillations of very long period the critical place would be one where the time interval is long, i.e. where the field is very weak and thus may be at a very great distance from the source; whilst for oscillations of very short period the critical place would be one where the time interval is short, i.e. where the force is very intense and thus, *ceteris paribus*, much closer to the source of oscillations than for the slow vibrations. We may illustrate this point by an example taken from the propagation of sound waves, which raises the same principle. Suppose that we have sound waves of a definite pitch travelling vertically upwards through the air and so getting into regions where the pressure gets lower and lower. As the pressure diminishes, the free path of the molecules increases and, with it, what is called the time of relaxation of the gas, i.e. the time taken by the gas to return to its normal condition after it has been disturbed from it. Suppose that the pressure gets so low that the time of relaxation is long compared with the period of the sound wave. It is clear, I think, that the sound would no longer be propagated, for if a condensation were to occur it would take so long to die away that it would persist until after a rarefaction was due. As this rarefied air cannot transmit the sound waves they will either be reflected back or converted into heat, and the energy of the sound will be confined to a finite volume instead of being dispersed through space.

As another illustration we may take one often used by Lord Kelvin. This is the case of a tightly stretched long string loaded at equal intervals with equal masses. This system has many periods. If P is the fastest of these, $P = \pi\sqrt{(lm/T)}$, where T is the tension in the string, m the mass of one of the particles loading the string, and l the distance between two adjacent particles. If one end of the string is agitated harmonically with a period p, waves will travel freely along the stretched string as long as P is less than p. If, however, the string is made more sluggish by increasing the mass of the particles or otherwise, so that p becomes less than P, the string will no longer transmit the waves and the energy instead of travelling along the string will be localized close to the extremity which is agitated. The

model would resemble the electrical case more closely if instead of spacing the particles at equal intervals the distance between two adjacent particles increased with the distance from one end A of the string; the value of P would increase with the distance from this end. If the end A were agitated harmonically with a period greater than the value of P close to A, but less than the value of P at some distance from A, the waves would travel along the string until they reached the place where P was equal to the period of agitation. Here they would be reflected back and the further parts of the string would be free from agitation.

To return to the case of the vibrating electron. We see that though it may send out electrical waves, these waves, after travelling through a distance which depends on the period of the vibrations and also upon their amplitude, will reach a region through which they cannot penetrate, and will be reflected back. Thus the energy emitted by the radiator will not travel out into space but will be reflected back and again absorbed by the radiator, and thus there will be no escape of energy.

If the oscillations were due to an electron describing a circular orbit, the reflected waves when they struck the electron and gave up their energy to it would, in general, deflect it and cause it to describe a different orbit. Thus the motion of the electron would not be steady. There may, however, be some orbits where the distance of the boundary at which the reflection takes place from the orbit is such that the reflected waves are in such a phase when they reach the electron that they just compensate for the changes in the motion of the electron produced by the emission of the radiation. For such orbits the uniform circular motion might be a steady state. It is evident that certain conditions have to be fulfilled for this to happen, so that it is only orbits with particular periods which possess this property. Since the application of a strong electric force would diminish the time-constant of the field, these orbits would be displaced by electric force. We may illustrate this point by the case of a piston vibrating at one end of an organ pipe which is closed at the other. In general, the waves reflected from the closed end will influence the motion of the piston, but they will not do so if the period of the piston is such that a loop of the vibrations of the pipe coincides with the position of the piston.

Let us apply similar considerations to light waves. Assuming that light is an electrical effect, we see at once that there can be no unlimited propagation of spherical electrical waves diverging from a source, such as is contemplated in the usual conception of the electromagnetic theory of light; for, on this view, energy in the light is distributed continuously through space and the energy per unit volume diminishes indefinitely as the light travels further and further away from the source. Now we have seen that the condition for the propagation of a periodic disturbance is that the period of the disturbance should be greater than the time interval of the electric field; this interval increases, however, as the energy in the light diminishes, so that when the energy falls below a certain value, which is small for long-period vibrations and large for short-period ones, any further propagation is impossible. Thus the intermittence of electrical force demands a corpuscular theory of light, i.e. a theory where the energy is done up in bundles which do not alter in size as they travel through space. The bundle may consist of a periodic distribution of electric force, like a piece cut out of what on the classical theory represents a beam of light. This piece is prevented from spreading because the energy density at its boundary has the critical value, and this boundary acts, on our view, like a reflecting surface and sends back any disturbance which tries to get outside it.

I picture these units as consisting of two parts: a central core in the form of an anchor ring, the plane of the ring being at right angles to the direction in which the unit is travelling. This ring is the seat of an intense electric field, and the circumference of the ring is equal to the wave-length of the light. This ring corresponds to the quantum of the light. This ring vibrates and emits electrical waves which, after travelling to a certain distance from the centre, get to the limit where the time interval of their electric field is equal to the period of the light. This forms the boundary of the unit, and the space occupied by the waves and the energy in them remain unaltered as the unit travels through space. On this view, light has a dual structure consisting of electrical waves with a quantum as the core. The electrical waves give rise to interference effects, the quanta to the photo-electric ones.

On the view that the force is intermittent the electric field must have a structure, and as electrons and positive particles are the centres of intense electric fields, they are probably much more complex than the usual conception of them and must be regarded as centres of complex systems associated with an electron or a positive particle. If we compare the atom with its electrons to a solar system, we may compare an electron or a positive particle to the centre of a nebula and regard the electron as surrounded by an atmosphere of small particles. This atmosphere can be distorted by the presence in its neighbourhood of other electrons or positive particles with their atmospheres, and will assume a shape appropriate to its surroundings. Thus the atmosphere round an electron, far from other charges, would be symmetrical and, if it were distorted, would vibrate about the symmetrical shape. Thus we could have vibrations associated with single electrons or single positively-charged particles, even though the electron or particle were itself at rest. Thus, for example, without becoming neutralized by the absorption of an electron a positively electrified hydrogen atom might be able to give out radiation. The possibility of vibrations of an electric field apart from any movement of the charges in the field has not, I think, been sufficiently realized.

These considerations suggest that just as matter is made up of molecules, and molecules are made up of electrons and positive particles, this is not the end of the story; there are still other worlds to conquer, the worlds which build up the electrons and positive particles.

THE PROBLEM OF THE SPHERICAL CONDENSER.*

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Summary.

Methods are given of computing to any desired accuracy the capacity of a spherical condenser when the bounding spherical surfaces are not concentric. Methods of calculating the attraction on the inner sphere and the maximum potential gradient in the field between the two shells are given. The results obtained are of use in calculating the capacity coefficients of spherical electrodes. They are directly useful also when measuring by standard methods the inductivity (specific inductive capacity), the thermal conductivity and the electrical conductivity of homogeneous substances.

The problem of the electrostatic condenser formed by two concentric spherical shells is familiar to every electrical engineer. If the radius of the outer shell be a and the radius of the inner shell be b, the capacity of the condenser is $\nu ab/(a - b)$, where ν is the inductivity (specific inductive capacity) of the medium between the two shells. When $(a - b)$ is small compared with b, the capacity of the condenser is large and can be very easily measured. Hence this formula gives us a method of measuring inductivity. It can also be used to measure thermal and electrical conductivities, as the mathematical theory of the problems is the same, the only difference being in the nature of the physical constants.

In practice, however, it is impossible to arrange so that the spherical shells are exactly concentric. As the radii of the spheres are nearly equal, a small error in the adjustment of their centres introduces an appreciable error into the results found by using the formula. For example, when Rosa and Dorsey * made a determination of the ratio of the electromagnetic to the electrostatic unit of charge they found it necessary, although their standard air condenser had been constructed with the greatest possible care, to take into account the fact that it was not quite concentric.

The complete solution of the problem, when the spheres are not concentric, is of practical importance from another point of view. It is proposed to use effective pressures exceeding a million volts in value for testing purposes. It is of importance, therefore, that we should be able to calculate without excessive labour the attractions and repulsions between the spherical electrodes whatever their potentials may be, and also the maximum value of the electric stress in the medium between them. At first sight this seems to have nothing to do with the problem discussed in this paper. The author, however, has shown * that the problem of finding the capacity coefficients of spherical conductors can always be reduced at once to that of finding the capacities of certain spherical condensers. They can, therefore, always be found by the help of the formulæ given in this paper. The author has published in the *Journal* † solutions for the case of equal spherical electrodes. The new methods which he now gives, and further methods which he hopes to give in a subsequent paper on the problem of external spheres, will partly supersede the formulæ previously given.

In certain experiments carried out by the late Mr. Duddell he used for the electrodes of his spark-gap a sphere and a hemispherical shell, the concavity of which was directed towards the sphere, and he asked the author to work out the problem of the maximum potential gradient in the spark-gap in this case. This the author did in the paper communicated to the Royal Society and referred to above. In that paper no proofs of the fundamental theorems are given. It is merely said that the formulæ are obtained by the method of images. Although this was a procedure sometimes adopted by Kelvin, the author thinks that much more rapid progress is made when elementary proofs of new theorems are given. In the following paper it is shown that the numerical values desired by electrical engineers can be computed to any required degree of accuracy by the use of elementary mathematics only. A few more advanced methods are given, however, when they lead to simpler or more accurate formulæ.

The mathematical results obtained by two quite different methods, similar to those used by Poisson and Kelvin for external spheres, both lead to the same system of inverse spheres. This system may possibly have some physical meaning. In any case it is of fundamental importance in making calculations, and so the author thinks that he is justified in giving complete mathematical proofs. He finds that it is unnecessary to introduce theorems taken from the Calculus of Finite Differences.

Concentric Spherical Condenser.

We shall denote a spherical condenser, the radii of the surfaces of which are b_0 and b_1, by (b_0, b_1, c_1), where c_1 is the distance between their centres. Its capacity we shall denote by $K(b_0, b_1, c_1)$, where c_1 is zero for concentric systems.

Let us first consider the case of a concentric spherical condenser (Fig. 1) of inner radius b_1 and outer radius

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† E. B. Rosa and N. E. Dorsey: "The Determination of the Ratio of the Electric Units," *Bulletin of the Bureau of Standards*, 1907, vol. 3, p. 477.

* A. Russell: "The Capacity Coefficients of Spherical Conductors," *Proceedings of the Royal Society*, A, 1920, vol. 97, p. 160.

† *Journal I.E.E.*, 1912, vol. 48, p. 257.

b_0. Construct another sphere concentric with both and of radius b_2, where $b_2 = b_1^2/b_0$. This sphere is the inverse of the outer sphere B_0 with respect to the sphere B_1. Similarly let B_3 be the inverse of B_1 with respect to B_2, and let $b_3 = b_2^2/b_1 = b_1^3/b_0^2$, etc. Then we have, when the medium is a vacuum,

$$K(b_0, b_1, 0) = b_0 b_1/(b_0 - b_1) = b_1 + b_1^2/b_0 + b_1^3/b_0^2 + \ldots$$
$$= b_1 + b_2 + b_3 + \ldots \qquad (1)$$

Similarly, $K(b_1, b_2, 0) = b_2 + b_3 + b_4 + \ldots$

and so we have

$$K(b_0, b_1, 0) = b_1 + K(b_1, b_2, 0)$$

and, in general,

$$K(b_{n-1}, b_n, 0) = b_n + K(b_n, b_{n+1}, 0) \qquad (2)$$

The radii of the spheres, $b_1, b_2, b_3 \ldots$ form a series

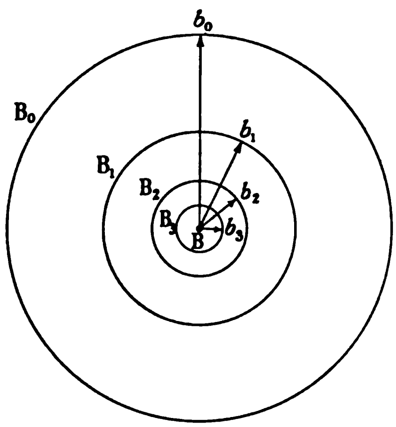

FIG. 1.—Concentric system of inverse spheres.

$$b_n^2 = b_{n-1} b_{n+1}$$
$$K(b_0, b_1, 0) = b_1 + b_2 + b_3 + \ldots = \frac{b_0 b_1}{b_0 - b_1}$$

in geometrical progression, the common ratio of which is b_1/b_0, and if this ratio is small, it is only necessary to compute a few terms of the series given by (1) in order to get a close approximation to its value. When $b_0, b_1, \ldots$ are measured in centimetres the formulæ give the capacity in C.G.S. units. To find the capacity in microfarads we have to divide this answer by 900 000.

If V be the potential difference between B_0 and B_1 (Fig. 1), the maximum value of the potential gradient between them is given by

$$R_{max.} = \frac{VK(b_0, b_1, 0)}{b_1^2}$$
$$= \frac{V}{b_1} + \frac{b_2 V}{b_1^2} + \frac{b_3 V}{b_1^2} + \ldots \qquad (3)$$

If $b_1, b_2, \ldots$ be measured in centimetres and V be in volts, $R_{max.}$ is given by (3) in volts per centimetre.

It will be seen later on that the formula (26) given for the capacity of a condenser when the spheres are not concentric is in agreement with (1), the successive inverse spheres being formed in a similar way but with their centres at definite distances apart. Formulæ (2) and (3) are also particular cases of (27) and (44).

The resultant mechanical force arising from the mutual electrical actions on the inner sphere must obviously be zero when the spheres are concentric, as there is no reason why it should move in one direction rather than another. We shall prove later on that the equilibrium in this case is unstable, as the inner sphere when displaced tends to move towards the outer one.

We shall now give a few geometrical theorems about inverse spheres as these are a great help in electrical problems of the nature under discussion.

The inverse spheres formed from two given spheres, one enclosing the other.—Let B_0 (Fig. 2) be the centre of the outer sphere, B_1 the centre of the inner sphere, and let b_0 and b_1 be their radii. Draw B_1QR cutting the two spheres in Q and R respectively. Join B_0R and produce B_0B_1 to D_0. Choose a point P on B_1R so that

$$B_1P \cdot B_1R = B_1Q^2 = b_1^2 \qquad (4)$$

Then P is the inverse of R with respect to the sphere whose centre is B_1.

We shall now prove that the locus of P is a sphere

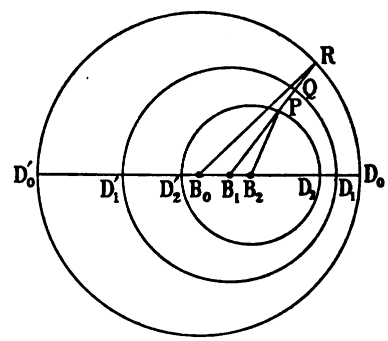

FIG. 2.

$B_1P \cdot B_1R = (B_1Q)^2$. The locus of P is a sphere whose centre is B_2.

of radius $b_0 b_1^2/(b_0^2 - c_1^2)$, where c_1 is the distance B_0B_1 between the centres of the spheres. The centre of this spherical locus is at a point B_2 on B_0B_1 produced, and $B_1B_2 = c_1 b_1^2/(b_0^2 - c_1^2)$.

If the angle PB_1B_2 be θ, we have by trigonometry

$$B_0R^2 = B_1R^2 + B_0B_1^2 + 2B_0B_1 \cdot B_1R \cos\theta$$

and hence $b_0^2 = b_1^4/r^2 + c_1^2 + 2(b_1^2 c_1/r)\cos\theta$

where $B_1P = r$.

Thus $b_0^2 - c_1^2 = b_1^4/r^2 + 2(b_1^2 c_1/r)\cos\theta$

and
$$r^2 = \frac{b_1^4}{b_0^2 - c_1^2} + \frac{2b_1^2 c_1 r\cos\theta}{b_0^2 - c_1^2}$$

and therefore

$$\frac{b_0^2 b_1^4}{(b_0^2 - c_1^2)^2} = r^2 + \frac{c_1^2 b_1^4}{(b_0^2 - c_1^2)^2} - \frac{2b_1^2 c_1 r\cos\theta}{b_0^2 - c_1^2} \qquad (5)$$

In Fig. 2, make $B_1B_2 = \dfrac{c_1 b_1^2}{b_0^2 - c_1^2} = c_2$. Then

$$B_2P^2 = r^2 + c_2^2 - 2rc_2\cos\theta \qquad (6)$$

Comparing (5) and (6) we get

$$B_2P = \frac{b_0 b_1^2}{b_0^2 - c_1^2} = \text{a constant} = b_2 \quad . \quad . \quad (7)$$

and

$$B_1B_2 = \frac{c_1 b_1^2}{b_0^2 - c_1^2} = c_2 \quad . \quad . \quad . \quad . \quad (8)$$

Thus the locus of P is a sphere with its centre at B_2. Since (Fig. 2) $B_1D_0 . B_1D_2 = b_1^2 = B_1D_0' . B_1D_1'$, we get

$$(b_0 - c_1)(b_2 + c_2) = b_1^2 = (b_0 + c_1)(b_2 - c_2) \quad . \quad (9)$$

Similarly we can take the inverse of the sphere D_1D_1' with regard to the sphere D_2D_2'. We shall denote its radius by b_3 and the distance B_2B_3 where B_3 is its centre by c_3. Proceeding in this way we see by (9) that the following relation connects b_n, b_{n-1}, b_{n-2}, c_n and c_{n-1}:

$$(b_{n-2}-c_{n-1})(b_n+c_n)=b_{n-1}^2=(b_{n-2}+c_{n-1})(b_n-c_n) \quad (10)$$

Thus, multiplying out, we get

$$c_n b_{n-2} = b_n c_{n-1} \quad . \quad . \quad . \quad . \quad (11)$$

and hence

$$c_n = \frac{b_n}{b_{n-2}} c_{n-1} = \frac{b_n}{b_{n-2}} \cdot \frac{b_{n-1}}{b_{n-3}} \cdot c_{n-2} = \ldots$$

$$= b_n b_{n-1} \frac{c_1}{b_1 b_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

From (10) and (11) we also find that

$$b_n b_{n-2} - b_{n-1}^2 = c_n c_{n-1}$$

and from (12)

$$\frac{1}{b_{n-1}^2} - \frac{1}{b_n b_{n-2}} = \left(\frac{c_1}{b_0 b_1}\right)^2 = \text{a constant.}$$

Hence

$$\frac{1}{b_{n-1}^2} - \frac{1}{b_n b_{n-2}} = \frac{1}{b_n^2} - \frac{1}{b_{n+1} b_{n-1}}$$

and

$$\frac{b_n}{b_{n-1}} + \frac{b_n}{b_{n+1}} = \frac{b_{n-1}}{b_{n-2}} + \frac{b_{n-1}}{b_n} = \ldots$$

$$= \frac{b_1}{b_0} + \frac{b_1}{b_2}$$

$$= \frac{b_0^2 + b_1^2 - c_1^2}{b_0 b_1} = \lambda \text{ (say)}$$

Therefore

$$\frac{1}{b_n} = \frac{\lambda}{b_{n-1}} - \frac{1}{b_{n-2}} \quad . \quad . \quad . \quad . \quad (13)$$

By the help of this formula the values of b_3, b_4, ... can be computed very easily in succession.

For example, suppose that $b_0 = 5$, $b_1 = 1$, and $c_1 = 1$. Then we have

$$\lambda = \frac{5^2 + 1^2 - 1^2}{5 \times 1} = 5$$

and thus

$$\frac{1}{b_2} = 5 - \tfrac{1}{5} = 4{\cdot}8, \quad \frac{1}{b_3} = 24 - 1 = 23,$$

$$\frac{1}{b_4} = 5 \times 23 - 4{\cdot}8 = 110{\cdot}2, \quad \frac{1}{b_5} = 551 - 23 = 528, \text{ etc.}$$

Hence, by a table of reciprocals,

$$b_2 = 0{\cdot}2083, \quad b_3 = 0{\cdot}04348,$$
$$b_4 = 0{\cdot}009074, \quad b_5 = 0{\cdot}001894, \text{ etc.}$$

A system of inverse spheres is cut at right angles by another sphere.—Let O (Fig. 3) be the centre of the sphere which cuts the spheres whose centres are B_n and B_{n+1} at right angles. Then if $c_{n+1} = B_nB_{n+1}$, we have

$$c_{n+1} = OB_n - OB_{n+1}$$
$$= \sqrt{(b_n^2 + r^2)} - \sqrt{(b_{n+1}^2 + r^2)} . \quad . \quad (14)$$

where r is the radius of the orthogonal sphere.

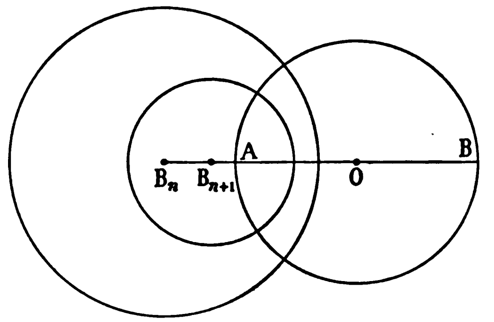

FIG. 3.—The sphere which cuts a given system of inverse spheres at right angles.

Hence by (12)

$$\sqrt{(b_n^2 + r^2)} - \sqrt{(b_{n+1}^2 + r^2)} = \frac{c_1}{b_0 b_1} . b_{n+1} b_n$$

and therefore

$$\sqrt{\left(\frac{1}{b_{n+1}^2} + \frac{r^2}{b_n^2 b_{n+1}^2}\right)} - \sqrt{\left(\frac{1}{b_n^2} + \frac{r^2}{b_n^2 b_{n+1}^2}\right)} = \frac{c_1}{b_0 b_1}$$

The value of the right-hand side of this equation is independent of the value of n. Thus, writing $n + 1$ for n, we get

$$\sqrt{(b_{n+1}^2 + r^2)} - \sqrt{(b_{n+2}^2 + r^2)} = \frac{c_1}{b_1 b_0} b_{n+1} b_{n+2} = c_{n+2} \quad (15)$$

Comparing (14) and (15), we see that r is also the radius of the orthogonal sphere which cuts the spheres whose centres are B_{n+1} and B_{n+2}. Hence it follows that the sphere whose radius is r and whose centre is at O cuts the two original spheres and all the inverse spheres at right angles.

We also have

$$\sqrt{(b_0^2 + r^2)} - \sqrt{(b_1^2 + r^2)} = c_1$$

and therefore

$$2c_1 r = [s(s - b_1)(s - c_1)(b_0 - s)]^{\frac{1}{2}} \quad . \quad . \quad (16)$$

where $2s = b_0 + b_1 + c_1$

The distance of its centre O from B_0 is $(r^2 + b_0^2)^{\frac{1}{2}}$, and the points A and B where it cuts the line of centres are inverse points of all the spheres. The point A gives the limiting position of the system of inverse spheres. We have

$$B_0A = (r^2 + b_0^2)^{\frac{1}{2}} - r$$

The value of B_0B_n.—Let us denote B_0B_n by x_n, then

$$x_n = c_1 + c_2 + \ldots + c_n$$

By (13),
$$1 = \frac{\lambda b_n}{b_{n-1}} - \frac{b_n}{b_{n-2}}$$
$$= \frac{\lambda b_n}{b_{n-1}} - \frac{c_n}{c_{n-1}} \text{ by (11)}$$

Thus
$$\frac{c_n + c_{n-1}}{c_{n-1}} = \lambda \frac{b_n}{b_{n-1}}$$

that is,
$$\frac{x_n - x_{n-2}}{b_n} = \lambda \frac{x_{n-1} - x_{n-2}}{b_{n-1}}$$

and hence by (13),
$$\frac{x_n}{b_n} = \lambda \frac{x_{n-1}}{b_{n-1}} - \frac{x_{n-2}}{b_{n-2}} \quad . \quad . \quad . \quad . \quad (17)$$

To compute the values of x_2, x_3, . . . etc., we first compute b_2, b_3, . . . by (13) and then find x_2, x_3, . . . in succession by (17).

If we put
$$\frac{x_n}{b_n} = \frac{l}{b_n} - \frac{m}{b_{n+1}}$$

where l and m are any constants, we see by (13) that (17) is satisfied. If we now determine l and m so that $x_0 = 0$, and $x_1 = c_1$, x_n will be the required value. Thus

$$0 = \frac{l}{b_0} - \frac{m}{b_1}$$
$$\frac{c_1}{b_1} = \frac{l}{b_1} - \frac{m}{b_2}$$

Thus
$$\frac{x_n}{b_n} = \frac{b_0^2}{c_1 b_n} - \frac{b_0 b_1}{c_1 b_{n+1}}$$

and therefore
$$\frac{b_{n+1}}{b_n} = \frac{b_0 b_1}{b_0^2 - c_1 x_n} \quad . \quad . \quad . \quad (18)$$

Inverse points.—Consider a spherical conductor (Fig. 4) maintained at zero potential and let there be a charge q of electricity at the point Q. Let O be the centre of the sphere and find a point Q′ in OQ such that OQ . OQ′ $= b_0^2$ where b_0 is the radius of the sphere. Take any point P on the sphere and join PO, PQ′ and PQ. Since OQ′/OP = OP/OQ and the triangles POQ and POQ′ have a common angle at O, they are equiangular, and thus

$$\frac{\text{OP}}{\text{PQ}'} = \frac{\text{OQ}}{\text{PQ}}$$

and hence
$$\frac{q}{\text{PQ}} - \frac{q(\text{OP}/\text{OQ})}{\text{PQ}'} = 0$$

Hence, if the spherical conductor were removed, the spherical surface would be the zero equipotential surface of the charges q and $-q$(OP/OQ) placed at Q and Q′ respectively. The electric field outside the spherical conductor is therefore exactly the same as if the conductor were removed and a point charge $-q$(OP/OQ) placed at Q′. From analogy Kelvin called Q′ the electrical image of Q, but it is necessary to remember that this image does not coincide with the optical image. When Q is at infinity, for example, the electrical image is at O, but the optical image would be at the middle point of the radius which lies on OQ. It is perhaps better, therefore, to call the point Q′ the inverse of Q.

Let us suppose that the sphere in Fig. 4 is electrified in some definite manner. Let us denote by $F(x/b_0)$ the

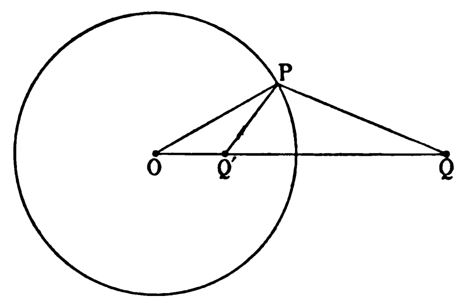

FIG. 4.
OQ . OQ′ = (OP)².

potential at the point Q, where OQ is x. Then if OQ . OQ′ $= b_0^2$, we have

$$F\left(\frac{x}{b_0}\right) = \sum \frac{\partial q}{\text{PQ}}$$

where ∂q is the element of the charge at P. We also have

$$\frac{\text{Q}'\text{P}}{\text{QP}} = \frac{\text{OP}}{\text{OQ}} = \frac{b_0}{x}$$

and hence

$$F\left(\frac{x}{b_0}\right) = \frac{b_0}{x} \sum \frac{\partial q}{\text{Q}'\text{P}} = \frac{b_0}{x} F\left(\frac{\text{OQ}'}{b_0}\right) = \frac{b_0}{x} F\left(\frac{b_0}{x}\right) \quad (19)$$

This relation, due to Poisson, is true for all values of x.

The Capacity of a Spherical Condenser.

Let B_0 (Fig. 5) be the centre of a spherical cavity in a conducting solid, and let B_1 be the centre of a spherical conductor in this cavity. Let $B_0B_1 = c_1$ and let the radii of the spheres be b_0 and b_1. Let the inner sphere have a charge q on its surface. It follows that there will be a charge $-q$ over the surface of the cavity. The potential at a point in the outer conductor at a great distance away from the cavity will be zero, for its distances from the charges $+q$ and $-q$ will be practically the same. Hence every point on the outer conductor must be at zero potential. We shall suppose that the inner conductor is at potential V. Let P

(Fig. 5) be any point on the line RB_0B_1Q inside the sphere whose centre is at B_1, and let $B_0P = x$. Let $F_1(x/b_0)$ be the potential at P produced by the charge $-q$, and let $F_2[(x-c_1)/b_1]$ be the potential at the same point produced by the charge $+q$, where c_1 denotes B_0B_1. Since the outer conductor is at zero potential, we get by considering the potential at any point Q in it on RB_1 produced,

$$F_1\left(\frac{B_0Q}{b_0}\right) + F_2\left(\frac{B_1Q}{b_1}\right) = 0$$

Hence, writing $B_0Q = \xi$, we get by (19)

$$\frac{b_0}{\xi}F_1\left(\frac{b_0}{\xi}\right) + \frac{b_1}{\xi - c_1}F_2\left(\frac{b_1}{\xi - c_1}\right) = 0 \quad . \quad (20)$$

where ξ is greater than b_0 or less than $-b_0$.

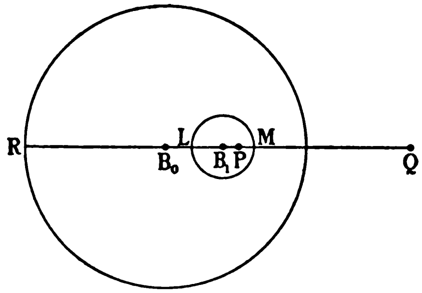

FIG. 5.
$B_0R = b_0$; $B_1M = b_1$; $B_0B_1 = c_1$
$K(b_0, b_1, c_1) = b_1 + b_2 + b_3 + \ldots$

At every point P inside the smaller sphere we have

$$F_1\left(\frac{x}{b_0}\right) + F_2\left(\frac{x - c_1}{b_1}\right) = V \quad . \quad . \quad . \quad (21)$$

where $B_0P = x$, and the values of x lie between $(c_1 - b_1)$ and $(c_1 + b_1)$.

Now consider pairs of points P and Q such that $B_0P \cdot B_0Q = b_0^2$ and so $x/b_0 = b_0/\xi$. Substituting for ξ in (20) we get

$$F_1\left(\frac{x}{b_0}\right) + \frac{b_0b_1}{b_0^2 - c_1x}F_2\left(\frac{b_1x}{b_0^2 - c_1x}\right) = 0$$

Subtracting this equation from (21), we get

$$F_2\left(\frac{x - c_1}{b_1}\right) - \frac{b_0b_1}{b_0^2 - c_1x}F_2\left(\frac{b_1x}{b_0^2 - c_1x}\right) = V \quad . \quad (22)$$

Now putting $x = x_1$, and writing

$$\frac{x_n - c_1}{b_1} = \frac{b_1x_{n-1}}{b_0^2 - c_1x_{n-1}} \quad . \quad . \quad . \quad (23)$$

an equation which enables x_n to be determined in terms of x_1; (22) becomes

$$F_2\left(\frac{x_1 - c_1}{b_1}\right) = V + \frac{b_0b_1}{b_0^2 - c_1x_1}F_2\left(\frac{x_2 - c_1}{b_1}\right)$$

Writing x_2 for x in (22) and substituting in this equation, and then writing x_3 for x, etc., we get

$$F_2\left(\frac{x_1 - c_1}{b_1}\right) = V\left\{1 + \frac{b_0b_1}{b_0^2 - c_1x_1} + \frac{b_0^2b_1^2}{(b_0^2 - c_1x_1)(b_0^2 - c_1x_2)} + \ldots\right\} \quad (24)$$

Since the values of $x_2, x_3, \ldots$ can be found in succession in terms of x_1 by (23), we see that (24) enables us to find the potential at any point on LM (Fig. 5) due to the distribution of the electricity q on its surface.

We have already seen by (18) that if $x_n = B_0B_n$, then

$$x_n = \frac{b_0^2}{c_1} - \frac{b_0b_1}{c_1} \cdot \frac{b_n}{b_{n+1}}$$

It readily follows from (13) that this value of x_n satisfies (23). Hence if we make $x_1 = c_1$, the values of x_n computed by (23) are the same as the values of x_n given by (18).

We have therefore

$$\frac{b_2}{b_1} = \frac{b_0b_1}{b_0^2 - c_1^2}; \quad \frac{b_3}{b_2} = \frac{b_0b_1}{b_0^2 - c_1x_2}; \quad \text{etc.}$$

Thus, substituting in (24), we get

$$F_2(0) = V\left(1 + \frac{b_2}{b_1} + \frac{b_2}{b_1} \cdot \frac{b_3}{b_2} + \frac{b_2}{b_1} \cdot \frac{b_3}{b_2} \cdot \frac{b_4}{b_3} + \ldots\right)$$
$$= \frac{V}{b_1}(b_1 + b_2 + b_3 + \ldots)$$

But the potential $F_2(0)$ at B_1 due to q is obviously q/b_1, since all the charge q is at the same distance b_1 from this point. Hence

$$q = V(b_1 + b_2 + b_3 + \ldots) \quad . \quad . \quad . \quad (25)$$

and since $\quad q = K(b_0, b_1, c_1)(V - 0)$

therefore

$$K(b_0, b_1, c_1) = b_1 + b_2 + b_3 + b_4 + \ldots \quad . \quad (26)$$

We see that the capacity of a spherical condenser equals the radius of the inner surface added to the sum of the radii of all the inverse spheres.

In many cases the formula (26) can be used directly to compute the value of $K(b_0, b_1, c_1)$. As a numerical example, take the case when $b_0 = 8$, $b_1 = 1$ and $c_1 = 3$.

Then $$\lambda = \frac{b_0^2 + b_1^2 - c_1^2}{b_0b_1} = 7$$

And by (13)

$$\frac{1}{b_2} = \frac{\lambda}{b_1} - \frac{1}{b_0} = 7 - \frac{1}{8} = \frac{55}{8}$$

$$\frac{1}{b_3} = \frac{385}{8} - 1 = \frac{377}{8}$$

$$\frac{1}{b_4} = 7 \times \frac{377}{8} - \frac{55}{8} = \frac{2\,584}{8}, \text{ etc., and thus}$$

$b_0 = 8$, $b_1 = 1$, $b_2 = 8/55$, $b_3 = 8/377$, $b_4 = 8/2\,584$, $b_5 = 8/17\,711$, $b_6 = 8/106\,266$, etc.

Thus $K(8, 1, 3)$

$$= 8\left(\frac{1}{8} + \frac{1}{55} + \frac{1}{377} + \frac{1}{2\,584} + \frac{1}{17\,711} + \frac{1}{106\,266} + \ldots\right)$$
$$= 1\cdot 1702993 \ldots$$

which is correct to the last figure.

When λ is small, however, this method is laborious. In this case it is better to proceed as follows. By (26) we have

$$K(b_1, b_2, c_2) = b_2 + b_3 + b_4 + \ldots$$

and thus

$$K(b_0, b_1, c_1) = b_1 + K(b_1, b_2, c_2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$
$$= b_1 + b_2 + K(b_2, b_3, c_3) \quad . \quad . \quad . \quad . \quad (28)$$
$$= b_2 + \ldots + b_n + K(b_n, b_{n+1}, c_{n+1}) \quad . \quad (29)$$

where by (12) $\qquad c_{n+1} = b_{n+1}b_nc_1/b_0b_1$

For example, using (28) and noticing that

$$K(ma, mb, mc) = mK(a, b, c),$$

we get $K(8, 1, 3) = 1 + \dfrac{8}{55} + \dfrac{8}{55 \times 377}K(377, 55, 3)$

Now the condenser $K(377, 55, 3)$ is approximately concentric and so, noticing that

$$K(377, 55, 0) = 377 \times 55/(377 - 55)$$

we get $\quad K(8, 1, 3) = 1 + 8/55 + 8/322$
$\qquad\qquad\qquad\quad = 1\cdot 1702993$ approximately,

the approximation being true to the last figure. If we had taken $n = 4$ in (29) a much closer approximation would have been obtained.

We can write (27) in the form *

$$K(b_0, b_1, c_1) = b_1 + \frac{b_1^2}{b_0^2 - c_1^2}K\left(\frac{b_0^2 - c_1^2}{b_1}, b_0, c_1\right) \quad (29a)$$

When b_1 is greater than c_1, we also have

$$K(b_0, b_1, c_1) = \frac{b_0^2}{b_1^2 - c_1^2}K\left(b_1, \frac{b_1^2 - c_1^2}{b_0}, c_1\right) - b_0 \quad . \quad (29b)$$

For example, by (29a)

$$K(7, 1, 1) = 1 + \tfrac{1}{48}K(48, 7, 1)$$
$$= 1 + 7/43 \text{ approximately}$$
$$= 1\cdot 163 \text{ approximately}$$

But expanding $K(48, 7, 1)$ in a similar way, we get

$$K(48, 7, 1) = 7 + \tfrac{1}{49}K(329, 48, 1)$$
$$= 7 + 7 \times 48/281$$

and thus

$$K(7, 1, 1) = 1 + 7/48 + 7/281 \text{ very approx.}$$
$$= 1\cdot 170743 \ldots$$

It can be shown that $K(b_0, b_1, c_1)$ is less than

$$b_1 + b_2 + \ldots + b_{n-1} + b_n\left[\frac{1}{2} + \frac{1}{2}\sqrt{\left(\frac{\lambda + 2}{\lambda - 2}\right)}\right] \quad (30)$$

* *Proceedings of the Royal Society*, A, 1920, vol. 97, p. 161.

where $\lambda = (b_0^2 + b_1^2 - c_1^2)/b_0b_1$ and $K(b_0, b_1, c_1)$ is greater than

$$b_1 + b_2 + \ldots + b_{n-1} + \frac{b_nb_{n-1}}{b_{n-1} - b_n} \quad . \quad (31)$$

For example, putting $n = 3$ in (30), we see that $K(8, 1, 3)$ is less than

$$1 + \frac{8}{55} + \frac{8}{377}\left(\frac{1}{2} + \frac{1}{2}\sqrt{\frac{9}{5}}\right)$$

which equals $1\cdot 1702994 \ldots$ but by (31) it is greater than $1\cdot 1702993 \ldots$

The accuracy of (30) and (31) is therefore quite satisfactory.

Equations Connecting the Capacities of Spherical Condensers.

It can be shown that, provided c be greater than 2, we always have

$K(c, 1, 1)$

$$= 1 + \frac{c}{c^2 - 1}K(c^2 - 1, 1, c) + \frac{1}{c^2 - 2}K(c^2 - 2, 1, 1) \quad . \quad (32)$$
$$= 1 + \frac{1}{c^2 - 1}K(c^2 - 1, c, 1)$$

For example, we have

$$K(3, 1, 1) = 1 + \tfrac{3}{8}K(8, 1, 3) + \tfrac{1}{7}K(7, 1, 1)$$
$$= 1\cdot 60611 \ldots$$

Substituting for $K(8, 1, 3)$ and $K(7, 1, 1)$ the values we found previously, we also see that

$$1 + \tfrac{1}{8}K(8, 3, 1) = 1\cdot 60611$$

and thus $\qquad K(8, 3, 1) = 4\cdot 8489$

This can be readily proved by (31).

The Resultant Electric Force on the Inner Sphere.

If W be the electrostatic energy stored in the condenser, we have

$$W = \frac{q^2}{2K(b_0, b_1, c_1)} = \tfrac{1}{2}K(b_0, b_1, c_1)V^2 \quad . \quad (33)$$

where $+\,q$ and $-\,q$ are the charges on the two surfaces and V is the difference of potential between them. It can be shown from (26) that $K(b_0, b_1, c_1)$ always increases as c_1 increases. Consequently if q remains constant W diminishes as the inner sphere approaches the outer one. If, however, V remains constant we see that W increases as c_1 increases. When the inner sphere is insulated, q is constant, and if no external forces are applied to the system we see by the conservation of energy that the resultant electric force acting on it must diminish W. By (33), therefore, $K(b_0, b_1, c_1)$ must increase and so the inner sphere moves towards the outer one.

If F be the force which acts in the direction of c_1

increasing, we have, when the charges are maintained constant,

$$F\partial c_1 = -\partial W$$

and so by (33)

$$F = \frac{q^2}{2[K(b_0, b_1, c_1)]^2}K'(b_0, b_1, c_1) \quad . \quad . \quad (34)$$

where $$K'(b_0, b_1, c_1) = \frac{\partial}{\partial c}[K(b_0, b_1, c_1)]$$

Hence also, by (33),

$$F = \tfrac{1}{2}V^2K'(b_0, b_1, c_1) \quad . \quad . \quad . \quad . \quad (35)$$

These expressions give the magnitude of the force F for any position of the inner sphere, the line of action of the force being the line joining the centres of the spheres.

We have now to show how the numerical value of $K'(b_0, b_1, c_1)$ can be computed. Using (31) and writing $\partial b_n/\partial c_1 = b_n'$, we get

$$K'(b_0, b_1, c_1) = b_2' + b_3' + \ldots + b_{n+1}' + \frac{b_n'/b_n^2 - b_{n-1}'/b_{n-1}^2}{(1/b_n - 1/b_{n-1})^2} \quad . \quad (36)$$

approximately.

The accuracy of the formula is higher the greater the value of n. In practice, not many terms are required and the calculation is not laborious. We first, by means of (13), compute in succession the values of $b_2, b_3 \ldots$

By differentiating (13) we get

$$\frac{b_n'}{b_n^2} = \lambda\frac{b_{n-1}'}{b_{n-1}^2} + \frac{2c_1}{b_0b_1}\cdot\frac{1}{b_{n-1}} - \frac{b_{n-2}'}{b_{n-2}^2} \quad . \quad . \quad (37)$$

Noticing that $b_1'/b_1^2 = 0$ and $b_2'/b_2^2 = 2c_1/b_0b_1^2$, we readily compute in succession $b_2', b_3' \ldots$

Hence by (36) and (34) or (35) we find F.

As an example, suppose that $b_0 = 5$, $b_1 = 1$ and $c_1 = 1$. Then by (31) and (13)

$$\begin{aligned} K(5, 1, 1) &= b_1 + b_2 + \ldots + b_6b_5/(b_6 - b_5) \\ &= 1 + \frac{10}{48} + \frac{1}{23} + \frac{10}{1\,102} + \frac{1}{528} + \frac{5}{10\,009} \\ &= 1\cdot263279 \end{aligned}$$

and thus $q = 1\cdot263279\ V$

By (37) $b_2'/b_2^2 = 2/5$, $b_3'/b_3^2 = 3\cdot92$, $b_4'/b_4^2 = 28\cdot4$, $b_5'/b_5^2 = 182\cdot16$ and $b_6'/b_6^2 = 1\,093\cdot6$.

$$\begin{aligned} \text{Thus } K'(5, 1, 1) &= 0\cdot0173611 + 0\cdot0074102 \\ &\quad + 0\cdot002386 + 0\cdot0006534 \\ &\quad + 0\cdot0002275 \\ &= 0\cdot0279908 \end{aligned}$$

$$\begin{aligned} \text{Hence} \quad F &= 0\cdot0139954V^2 \\ &= 0\cdot00876973q^2 \end{aligned}$$

It must be noticed that the lengths $b_0, b_1, \ldots$ are measured in centimetres and that q and V are in electrostatic units. In this case F is in dynes. If V is in volts, all we have to do is to divide it by 300, so as to reduce it to electrostatic units. Similarly if q is given in coulombs we must multiply its value by 3×10^9. To reduce $K(a, b, c)$ to microfarads we divide by 900 000.

Simplified formulæ.—Putting $n = 3$ in (36), and using (35), we get

$$\frac{F}{V^2} = \frac{c_1b_0b_1^2}{(b_0^2 - c_1^2)^2} + \frac{[(2\lambda - 1)b_0 - b_1]c_1}{[(\lambda^2 - \lambda - 1)b_0 - (\lambda - 1)b_1]^2} \quad (38)$$

Applying this formula to the condenser (5, 1, 1) we get

$$F = 0\cdot013994V^2$$

the error being less than 1 in 10 000.

If V is in volts, we must divide it by 300 before substituting, so as to get F in dynes. The following formula * is sometimes given for $K(b_0, b_1, c_1)$. It is applicable when $c_1/(b_0 - b_1)$ is small.

$$K(b_0, b_1, c_1) = \frac{b_0b_1}{b_0 - b_1}\left\{1 + \frac{b_0b_1}{b_0^2 + b_0b_1 + b_1^2}\cdot\frac{c_1^2}{(b_0 - b_1)^2}\right\} \quad (38a)$$

We deduce by (35) that

$$\frac{F}{V^2} = \frac{b_0^2b_1^2c_1}{(b_0^3 - b_1^3)(b_0 - b_1)^2}$$

These formulæ make $K(5, 1, 1) = 1\cdot2626 \ldots$ and $F/V^2 = 0\cdot01260 \ldots$ The error in the capacity formula is about 6 in 10 000, but in the force formula it is nearly 10 per cent.

When the spheres are at a microscopic distance x apart, we have †

$$F = \frac{b_0b_1V^2}{4(b_0 - b_1)x} \quad . \quad . \quad . \quad . \quad (39)$$

The Maximum and Minimum Potential Gradients at the Surface of the Inner Sphere.

The maximum ($R_{max.}$) and the minimum values of the potential gradients at the surface of the inner sphere occur at the points L and N respectively (Fig. 6) where the line joining the centres of the spheres cuts the inner sphere. The most direct way of getting a series for them is to use Kelvin's method of images.‡ By this method we show that if a series of point charges $q_1, q_2, \ldots q_1', q_2', \ldots$ be placed at the points $B_1, B_2, \ldots B_1', B_2', \ldots$ respectively (Fig. 6), then if the points and charges be properly chosen and the conducting spheres be removed, the electric field produced by these charges will have the original surfaces of the spheres for equipotential surfaces. By choosing the charges properly, we can make the equipotential surface through L at potential V and the one through M at zero potential. These surfaces may become conducting without upsetting the equilibrium of the field. Hence the field produced by the given point charges will be the same as the actual field.

* J. H. Jeans: "Electricity and Magnetism." Also L. Cohen: "Alternating-Current Problems."
† *Proceedings of the Royal Society*, A, 1917–18, vol. 94, p. 215.
‡ A. Russell: "Alternating Currents," vol. 1, p. 236.

The points are connected by the following relations :—

$$B_0B_1 \,.\, B_0B_1' = b_0^2\,;\quad B_1B_1' \,.\, B_1B_2 = b_1^2$$
$$B_0B_2 \,.\, B_0B_2' = b_0^2\,;\quad B_1B_2' \,.\, B_1B_3 = b_1^2$$
$$\cdots\cdots\cdots\cdots$$
$$B_0B_n \,.\, B_0B_n' = b_0^2\,;\quad B_1B_n' \,.\, B_1B_{n+1} = b_1^2 \quad . \quad (40)$$

Thus if $B_0B_n = x_n$, we get by (40)

$$x_n\left(\frac{b_1^2}{x_{n+1} - c_1} + c_1\right) = b_0^2$$

and therefore $\dfrac{x_{n+1} - c_1}{x_n} = \dfrac{b_1^2}{b_0^2 - c_1x_n}$

We see that this equation is the same as (23), and since $x_1 = c_1$, we have

$$x_n = c_1 + c_2 + \ldots + c_n$$

The points B_2, B_3, . . . are therefore the centres of

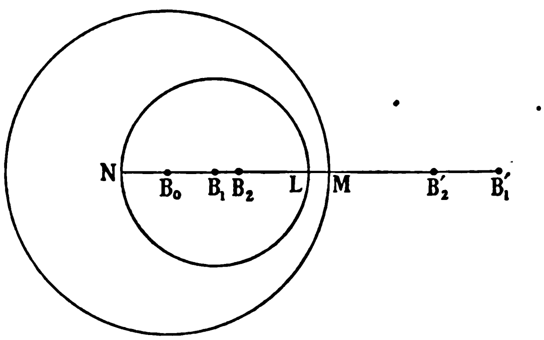

FIG. 6.

The equivalent point charges $q_1, q_2 \ldots q_1', q_2' \ldots$ are placed at $B_1, B_2, \ldots B_1', B_2', \ldots$ where

$$B_0B_1 \,.\, B_0B_1' = b_0^2\,;\quad B_1B_1' \,.\, B_1B_2 = b_1^2$$
$$\frac{q_1}{B_1M} = -\frac{q_1'}{B_1'M}\,;\quad \frac{q_2}{B_2L} = -\frac{q_1'}{B_1'L}$$

the series of inverse spheres previously considered. We also have

$$\frac{b_0b_1}{b_0^2 - c_1x_n} = \frac{x_{n+1} - c_1}{x_n} \cdot \frac{b_0}{b_1} = \frac{b_{n+1}}{b_n} \quad . \quad (41)$$

by (18), where b_n is the radius of the nth inverse sphere.

If we make the charge q_1 at B_1 equal to b_1, the potential of the inner sphere will be unity. To make the potential of the outer one equal to zero, we must place a charge q_1' at B_1', where

$$\frac{q_1}{B_1M} = \frac{-q_1'}{B_1'M}$$

Similarly, to reduce the inner sphere again to unity potential we place a charge q_2 at B_2 and make

$$\frac{q_2}{B_2L} = \frac{-q_1'}{B_1'L}$$

Thus $$\frac{q_2}{q_1} = \frac{B_2L}{B_1'L} \cdot \frac{B_1'M}{B_1M}$$

In general,

$$\frac{q_{n+1}}{q_n} = \frac{B_{n+1}L}{B_n'L} \cdot \frac{B_n'M}{B_nM}$$
$$= \frac{b_1 + c_1 - x_1}{b_1^2/(x_{n+1} - c_1) - b_1} \cdot \frac{(b_0^2/x_n) - b_0}{b_0 - x_n}$$
$$= \frac{x_{n+1} - c_1}{x_n} \cdot \frac{b_0}{b_1}$$
$$= \frac{b_{n+1}}{b_n}, \text{ by (41).}$$

Since $q_1 = b_1$, we see that $q_n = b_n$.

Hence the charges q_1, q_2, . . . are placed at B_1, B_2, . . . the centres of the inverse spheres, and their magnitudes equal b_1, b_2, . . . the radii of these spheres.

We can now write down the value of the maximum potential gradient $R_{max.}$ which occurs at L. We have

$$R_{max.} = \frac{q_1}{B_1L^2} + \frac{q_2}{B_2L^2} + \frac{q_3}{B_3L^2} + \ldots$$
$$- \frac{q_1'}{B_1'L^2} - \frac{q_2'}{B_2'L^2} - \frac{q_3'}{B_3'L^2} - \ldots$$

We also have

$$\frac{q_2}{B_2L} = -\frac{q_1'}{B_1'L},\quad \frac{q_3}{B_3L} = -\frac{q_2'}{B_2'L}, \ldots$$

Thus

$$R_{max.} = \frac{q_1}{b_1^2} + \frac{q_2}{B_2L}\left(\frac{1}{B_2L} + \frac{1}{B_1'L}\right) + \frac{q_3}{B_3L}\left(\frac{1}{B_3L} + \frac{1}{B_2'L}\right) + \ldots$$
$$= \frac{q_1}{b_1^2} + \frac{q_2(b_1 + d_2)}{b_1(b_1 - d_2)^2} + \frac{q_3(b_1 + d_3)}{b_1(b_1 - d_3)^2} + \ldots \quad . \quad (42)$$

where $d_n = x_n - c_1$, so that by (23)

$$\frac{b_1^2}{d_n} = \frac{b_0^2}{d_{n-1} + c_1} - c_1 \quad . \quad . \quad . \quad . \quad (43)$$

If we make $q_1 = Vb_1$, $q_2 = Vb_2$, . . . the potential difference across the spherical condenser will be V. In this case we have

$$R_{max.} = \frac{V}{b_1}\left\{1 + \frac{b_2(b_1 + d_2)}{(b_1 - d_2)^2} + \frac{b_3(b_1 + d_3)}{(b_1 - d_3)^2} + \ldots \right.$$
$$\left. + \frac{b_n(b_1 + d_n)}{(b_1 - d_n)^2} + \ldots\right\} \quad . \quad (44)$$

Similarly for the minimum potential gradient at N, we have

$$R_{min.} = \frac{V}{b_1}\left\{1 + \frac{b_2(b_1 - d_2)}{(b_1 + d_2)^2} + \frac{b_3(b_1 - d_3)}{(b_1 + d_3)^2} + \ldots\right\} \quad (45)$$

The computation of the values of $R_{max.}$ and $R_{min.}$ can be simplified by noticing that the value of d_n increases very slowly with n when n is large. If d be the value of d_n, when d is infinite it will equal B_1A, A being the point where the orthogonal sphere cuts the line B_0B_1 produced. If r be the radius of this sphere,

$$d(d + 2r) = b_1^2$$

and thus

$$d = (b_1^2 + r^2)^{\frac{1}{2}} - r \quad . \quad . \quad . \quad . \quad (46)$$

If X_n denote the remainder of the series given in (44) after n terms, we have

$$X_n = \frac{(b_{n+1} + b_{n+2} + \ldots)(b_1 + d)}{(b_1 - d)^2}$$
$$= \frac{(K - b_1 - \ldots - b_n)(b_1 + d)}{(b_1 - d)^2} \quad . \quad (47)$$

approximately. This approximation makes $R_{max.}$ slightly too great. But if we substitute d_{n+1} for d in (47) the value found will be slightly too small. We thus find limits between which the true value must lie.

Numerical example.—Let us consider the condenser (5, 2, 2). Noticing that $b_0 = 5$, $b_1 = 2$, $c_1 = 2$ we get $\lambda = 5/2$, and thus by (13)

$$b_2 = 20/21,\ b_3 = 8/17,\ b_4 = 80/341,\ b_5 = 32/273$$

and by (43), since $d_1 = 0$, we get

$$d_2 = 8/21,\ d_3 = 8/17,\ d_4 = 168/341,\ d_5 = 136/273$$

and, by (16), $r = 15/4$ and therefore, by (46), $d = \frac{1}{2}$. It will be noticed that there is little difference between d and d_5. It is unnecessary, therefore, to go to high values of n.

Taking $n = 5$, we find by (31) that

$$K = 3 \cdot 891981$$

[If we had used (38*a*) we should have found that $K = 3 \cdot 7132$.]

Hence by (44) and (47) we see that $R_{max.}/V$ is less than

$$\frac{1}{2} + \frac{10}{21} \cdot \frac{(2 + 8/21)}{(2 - 8/21)^2} + \ldots + X_5$$

where $X_5 = 0 \cdot 13023$, and thus $R_{max.}$ is less than $1 \cdot 43998V$. Similarly it is greater than $1 \cdot 43957V$. The true value found by (58) given below is $1 \cdot 43973$. The geometrical method, therefore, is sufficiently accurate for practical work. Similarly we find that $R_{max.}$ lies in value between $0 \cdot 75162V$ and $0 \cdot 75154V$. Its true value is $0 \cdot 75159V$.

Hyperbolic Functions.

Some of the formulæ given previously can be written very conveniently in terms of hyperbolic functions.* We denote the new variables by α, β and ω, and define them as follows:—

$$\cosh \alpha = \frac{b_0^2 + c_1^2 - b_1^2}{2b_0c_1}$$
$$\cosh \beta = \frac{b_0^2 - b_1^2 - c_1^2}{2b_1c_1}$$

and
$$\cosh \omega = \frac{b_0^2 + b_1^2 - c_1^2}{2b_0b_1} = \frac{\lambda}{2}$$

It follows from these equations that $\beta = \alpha + \omega$, $\sinh \alpha = r/b_0$, $\sinh \beta = r/b_1$ and $\sinh \omega = c_1r/b_0b_1$, where r is the radius of the sphere cutting at right angles the spheres and the system of inverse spheres. It then follows from (13) that $b_n = r/\sinh(\alpha + n\omega)$, and thus by (26)

$$K(b_0, b_1, c_1) = \frac{r}{\sinh \beta} + \frac{r}{\sinh(\beta + \omega)} + \frac{r}{\sinh(\beta + 2\omega)} + \ldots \quad . \quad (48)$$

This can also be written in the form,

$$K(b_0, b_1, c_1) = b_1 + \frac{b_0b_1^2}{d^2} + \frac{b_0^2b_1^3}{d^4 - b_1^2c_1^2} + \frac{b_0^3b_1^4}{d^2(d^4 - 2b_1^2c_1^2) - b_0^4c_1^2} + \ldots \quad . \quad (49)$$

where $d^2 = b_0^2 - c_1^2$. As a rule it is less laborious to calculate $b_2, b_3 \ldots$ successively by (13). When, however, the spheres are close together, the following modification of (49) obtained by a method previously described * is useful.

$$K(b_0, b_1, c_1) = b_1 + \frac{b_0b_1^2}{d^2} + \frac{b_0^2b_1^3}{d^4 - b_1^2c_1^2} + \frac{b_0b_1}{c_1}(m + 1)\left\{\frac{1}{nm^3} + \frac{1}{n^3m^7(m^2 + m + 1)} + \frac{1}{n^5m^{11}(m^4 + m^3 + m^2 + m + 1)} + \ldots\right\} \quad (50)$$

where $n = \dfrac{r}{b_1} + \dfrac{\sqrt{(r^2 + b_1^2)}}{b_1}$, $m = \dfrac{b_0n}{c_1 + b_1n}$

$$c_1r = 2\{s(b_0 - s)(s - b_1)(s - c_1)\}^{\frac{1}{2}},$$

and
$$2s = b_0 + b_1 + c_1 \quad . \quad . \quad . \quad . \quad (51)$$

For example, let us suppose that $b_0 = 10$, $b_1 = 1$, and $c_1 = 7$. By (51), $7r = 24$, $n = 7$, and $m = 5$. Thus by (50)

$$K(10, 1, 7) = 1 + \frac{10}{51} + \frac{100}{2\,552} + \frac{12}{1\,225} + \frac{12}{35^4 \times 25 \times 31} + \ldots$$
$$= 1 \cdot 2450593 \ldots$$

It will be seen that the series is rapidly convergent. The capacity in this case can also be readily computed by (29*a*). Thus

$$K(10, 1, 7) = 1 + \tfrac{1}{51}K(51, 10, 7)$$
$$= 1 + \frac{10}{51} + \frac{100}{51 \times 2552}K(2552, 51, 7)$$
$$= 1 \cdot 2450593.$$

When $b_0 - b_1 - c_1$ is very small, so that the spheres are nearly touching, we get

$$K(b_0, b_1, c_1) = \frac{r}{\omega}\left\{-\psi\left(\frac{\beta}{\omega}\right) + \log_e \frac{2}{\omega} + \frac{\omega^2}{72} + \frac{7\omega^4}{43\,200} + \ldots + \frac{\alpha\beta}{12} - \frac{7\alpha^2\beta^2}{1\,440} + \ldots\right\} \quad . \quad (52)$$

* Cf. MAXWELL, vol. 1, § 173; and *Journal I.E.E.*, 1926, vol. 64, p. 240.

* *Proceedings of the Royal Society*, A, 1917–18, vol. 94, p. 108.

where $\psi(x)$ is a function the values of which can be found either by the formulæ or from the table given in Russell's "Alternating Currents," vol. 1, pp. 240 and 241. The values of α, β and ω can be found either from their definitions or by noticing that $\beta = \log_\epsilon n$, $\omega = \log_\epsilon m$ and $\alpha = \beta - \omega$. When $b_1 = c_1$, (52) becomes

$$K(b_0, b_1, b_1) = \frac{r}{\omega}\left\{\gamma + \log_\epsilon \frac{2}{\omega} + \frac{\omega^2}{72} + \frac{7\omega^4}{43\,200} + \dots\right\} - b_0 \quad (52a)$$

where γ is Euler's constant $(0{\cdot}577216\dots)$.

When the distance between the spheres is microscopic we can use the formula *

$$K(b_0, b_1, c_1) = \frac{b_0 b_1}{b_0 - b_1}\left\{\tfrac{1}{2}\log_\epsilon \frac{2b_0 b_1}{(b_0 - b_1)(b_0 - b_1 - c_1)} - \psi\left(\frac{b_0}{b_0 - b_1}\right)\right\} \quad (53)$$

By differentiating (48) we get for the mutual force F,

$$F = \frac{V^2}{2}\left\{\sum_1^\infty n \frac{\cosh(\beta + n\omega)}{\sinh^2(\beta + n\omega)} - \frac{\cosh\alpha\cosh\beta}{\sinh\omega}\sum_0^\infty \frac{1}{\sinh(\beta + n\omega)} + \frac{\sinh\beta\cosh\alpha}{\sinh\omega}\sum_0^\infty \frac{\cosh(\beta + n\omega)}{\sinh^2(\beta + n\omega)}\right\} \quad . \quad (54)$$

and this can be put into forms more suitable for computation in special cases.

Noticing that $b_n = \dfrac{r}{\sinh(\alpha + n\omega)}$

and that $d_n = \dfrac{b_1 \sinh(n-1)\omega}{\sinh(\alpha + n\omega)}$

(44) and (45) become

$$R_{max.} = \frac{V}{b_1}\left(\frac{\cosh^2 \frac{1}{2}\beta}{\sinh \frac{1}{2}\beta}\right)\left[\frac{\sinh\frac{1}{2}\beta}{\cosh^2\frac{1}{2}\beta} + \frac{\sinh(\frac{1}{2}\beta + \omega)}{\cosh^2(\frac{1}{2}\beta + \omega)} + \frac{\sinh(\frac{1}{2}\beta + 2\omega)}{\cosh^2(\frac{1}{2}\beta + 2\omega)} + \dots\right] \quad . \quad (55)$$

and

$$R_{min.} = \frac{V}{b_1}\left(\frac{\sinh^2 \frac{1}{2}\beta}{\cosh \frac{1}{2}\beta}\right)\left[\frac{\cosh\frac{1}{2}\beta}{\sinh^2\frac{1}{2}\beta} + \frac{\cosh(\frac{1}{2}\beta + \omega)}{\sinh^2(\frac{1}{2}\beta + \omega)} + \frac{\cosh(\frac{1}{2}\beta + 2\omega)}{\sinh^2(\frac{1}{2}\beta + 2\omega)} + \dots\right] \quad . \quad (56)$$

* *Proceedings of the Royal Society*, A, 1917–18, vol. 94, p. 212.

The following series deducible from (55) and (56), although they look clumsy, are rapidly convergent and are suitable for computing purposes even when the spheres are very near one another.

$$R_{max.} = \frac{V}{b_1}\left\{1 + \frac{b_0 b_1[b_0^2 - c_1(c_1 - b_1)]}{[b_0^2 - c_1(c_1 + b_1)]^2} + \epsilon^{-\omega}\frac{(1 + \epsilon^{-\beta})^2}{1 - \epsilon^{-\beta}}\left[\frac{\epsilon^{-\omega}}{1 - \epsilon^{-\omega}} - 3\frac{\epsilon^{-3\omega}}{1 - \epsilon^{-3\omega}}\epsilon^{-(\beta+2\omega)} + 5\frac{\epsilon^{-5\omega}}{1 - \epsilon^{-5\omega}}\epsilon^{-2(\beta+2\omega)} - \dots\right]\right\} \quad . \quad . \quad . \quad (57)$$

and

$$R_{min.} = \frac{V}{b_1}\left\{1 + \frac{b_0 b_1[b_1^2 - c_1(c_1 + b_1)]}{[b_0^2 - c_1(c_1 - b_1)]^2} + \epsilon^{-\omega}\frac{(1 - \epsilon^{-\beta})^2}{1 + \epsilon^{-\beta}}\left[\frac{\epsilon^{-\omega}}{1 - \epsilon^{-\omega}} + 3\frac{\epsilon^{-3\omega}}{1 - \epsilon^{-3\omega}}\epsilon^{-(\beta+2\omega)} + 5\frac{\epsilon^{-5\omega}}{1 - \epsilon^{-5\omega}}\epsilon^{-2(\beta+2\omega)} + \dots\right]\right\} \quad . \quad . \quad . \quad (58)$$

where $\epsilon^{-\beta} = \cosh\beta - \sinh\beta = \left(1 + \dfrac{r^2}{b_1^2}\right)^{\frac{1}{2}} - \dfrac{r}{b_1}$

and $\epsilon^{-\omega} = \left(1 + \dfrac{c_1^2 r^2}{b_0^2 b_1^2}\right)^{\frac{1}{2}} - \dfrac{c_1 r}{b_0 b_1}$

As an example, consider the condenser (5, 2, 2). In this case $\epsilon^{-\omega} = \frac{1}{2}$, $\epsilon^{-\beta} = \frac{1}{4}$, and so, substituting in (57), we get

$$\begin{aligned} R_{max.} &= \frac{V}{2}[1 + 0{\cdot}8650520 + \tfrac{25}{24}(1 - 0{\cdot}0267857 \\ &\qquad + 0{\cdot}0006301 - 0{\cdot}0000135 \\ &\qquad + 0{\cdot}0000003 - \dots)] \\ &= 1{\cdot}4397297V \end{aligned}$$

If we write x for $b_0 - b_1 - c_1$ and neglect cubes and higher powers of $c_1/(b_0 - b_1)$, we find, after laborious algebraical work, that

$$R_{max.} = \left\{1 + \frac{(2b_0 + b_1)x}{3b_0 b_1} + \frac{[4(b_0 + b_1)^2 - b_0 b_1]x^2}{45 b_0^2 b_1^2}\right\}\frac{V}{x} \quad (59)$$

As an example, let $b_0 = 5$, $b_1 = 2$, $c_1 = 2$, so that $x = 1$, and $c_1/(b_1 - b_0) = \frac{1}{3}$.

In this case $R_{max.} = 1{\cdot}4413V$.

Comparing with the true value found above, we see that although $c_1/(b_1 - b_0)$ is as great as $\frac{1}{3}$, the error introduced by using (59) is only about 1 in 704. For smaller values of x the accuracy is much higher.

A METHOD OF OBSERVING FLAWS IN METAL SURFACES AND OF COMPARING THE CONDUCTIVITIES OF METAL PLATES.*

By Professor E. W. Marchant, D.Sc., Member, and J. L. Miller, B.Eng., Student.

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Summary.

This paper describes an apparatus which has been developed for observing, by a direct deflection method, small changes in the effective resistance and inductance of a coil. It consists of a bridge network, with two inductive arms, which is normally balanced. The bridge is supplied with alternating currents, the indicating instrument being a d.c. galvanometer connected through a synchronously driven commutator. One of the arms of the bridge contains the "exploring" coil, which is placed on the metal surface to be examined. It is shown that if the commutator is so adjusted as to indicate the current in phase with the applied voltage, its deflection is proportional to the change in effective resistance of the exploring coil. With the commutator adjusted to observe currents 90° out of phase with the applied voltage, the deflection depends on the change in effective inductance of the coil, when this change is brought about by the presence of a metal plate. For non-magnetic materials it is best to use the commutator in the "out of phase" position. The change in effective inductance depends on the specific conductivity of the plate, and the apparatus may be used for quickly comparing the specific conductivities of metal plates. If such plates have cracks normal to the surface, their presence is indicated by a reduction in the galvanometer deflection as the coil passes over a crack. For magnetic materials the commutator should be set in the "in phase" position. Cracks in magnetic materials can be observed in the same way as those in non-magnetic materials.

Table of Contents.

(1) Principle of Action of the Apparatus.

When a coil of wire, through which an alternating current is flowing, is brought near a piece of metal, currents are induced in the metal which have the effect of producing an apparent increase in the impedance of the primary coil, the change in the impedance being a function of the resistance offered by the metal to the induced secondary currents.† The resistance offered to the induced secondary currents depends on the conductivity and thickness of the metal plate, and if the change in effective resistance or inductance of the coil is measured, the change in resistance or inductance will enable the conductivity of the metal plate to be estimated for a given size and shape of coil.

The apparatus is arranged as follows: The coil, which will, throughout the paper, be called the "exploring coil," is so connected as to form one arm of an ordinary Wheatstone bridge network, of which a coil, having the same resistance and inductance as the exploring coil, forms the third arm. The "proportional" arms are non-inductive resistances, and are made equal to each other. The two inductive arms are also made as nearly similar to each other as possible. The bridge is supplied with constant frequency alternating current at constant voltage, and is balanced approximately.

When the exploring coil is placed on a metal plate, its effective impedance is altered, and thus the balance of the bridge is disturbed; a current depending on the total impedance change therefore flows through the galvanometer circuit.

In Fig. 1 (*a*) is shown the diagram of connections. BD is the exploring coil, whose resistance and inductance are respectively R_4 and L_4, AD being an exactly similar coil. CB and CA are the two non-inductive resistances which form the proportional arms.

A small alternator or rotary converter is connected across CD and supplies the bridge with the necessary alternating current. A galvanometer is connected across AB, the connection being made through a two-part commutator driven synchronously by an extension of the shaft of the alternator.

If the brush gear is rocked round the commutator, there is one position where the rectified current is in phase with the impressed voltage, and another position 90 electrical degrees removed from the former, where the rectified current is 90° out of phase with the impressed voltage, and it will be shown later mathematically that in the former position the deflection of the galvanometer is proportional to the change in effective resistance of the coil, and is in the latter position proportional to the change in effective inductance of the coil. As already explained, if a metal plate is brought near to the coil R_4 L_4 there is a deflection of the galvanometer, which is proportional to the effective resistance or inductance change, according to the position in which the brush rocker may be. If the brush rocker is set in such a position that the deflection of the galvanometer is due to change in effective resistance only, and the resistance of one of the arms is altered by a

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† Cf. Hughes: *Journal I.E.E.*, 1886, vol. 15, p. 6.

known amount and the galvanometer deflection observed, then the effective resistance-change for a known galvanometer deflection is determined. In the same way, by inserting a known, small inductance in one of the arms, the change in effective inductance of the coil corresponding to a given galvanometer deflection can be determined with the brushes in the out-of-phase position. By means of this calibration the change in effective resistance or inductance of the exploring coil under any conditions can be measured.

The apparatus under consideration is not only suitable for measuring the change in effective resistance or inductance of a coil due to the presence of a metal plate, but can readily be used to detect flaws and cracks in the plate, since the slightest crack in the metal is sufficient to put a very high resistance in the path of the induced secondary currents in the material of which the plate is made, hence causing a change in the balance of the bridge.

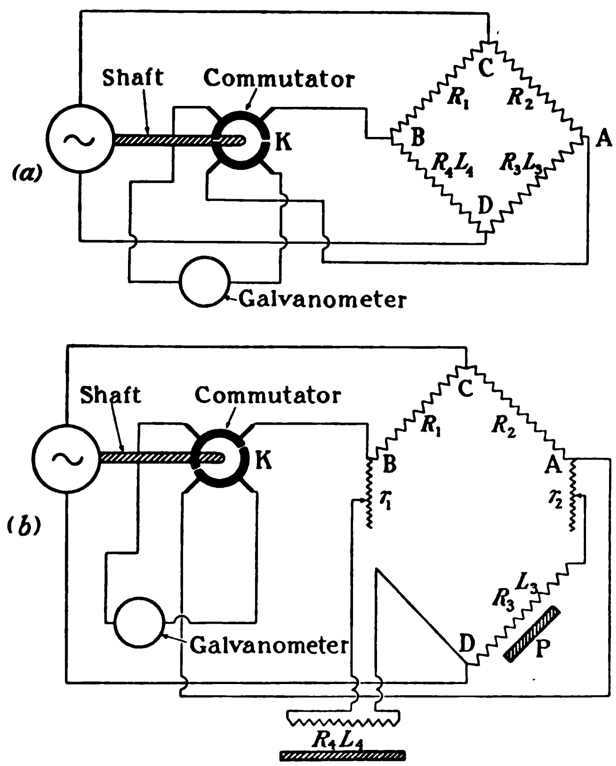

FIG. 1.—Diagram of connections.

(2) DESIGN AND METHOD OF USE OF APPARATUS.

(*a*) *Early form of apparatus.*—In Fig. 1 (*b*) is shown the actual connection of the early form of the apparatus. K is the two-part commutator driven synchronously from the shaft of a 4-pole rotary converter. The rotary converter is separately excited, and when so arranged both its speed and voltage can be readily controlled. R_1 and R_2 are the two non-inductive resistances each of about 10 ohms resistance, while L_3, R_3, and L_4, R_4, are the two inductive resistances, also of about 10 ohms resistance.

In series with L_3, R_3, and L_4, R_4, are the two sets of adjustable resistances r_1 and r_2 which were used to balance the bridge. For fine adjustment, a metal plate P could be brought near the coil L_3, R_3, thus altering its effective impedance and providing a very simple method of controlling the zero of the galvanometer. The exploring coil R_4, L_4, was connected to the bridge by a length of flexible cable. Fig. 2 shows the arrangement actually used in the early tests with the commutator.

The "radial arm" variable resistances used for balancing purposes are shown as r_1 and r_2, and P is the adjustable metal plate. The letters in Fig. 2 correspond to those in Fig. 1. The three bridge arms,

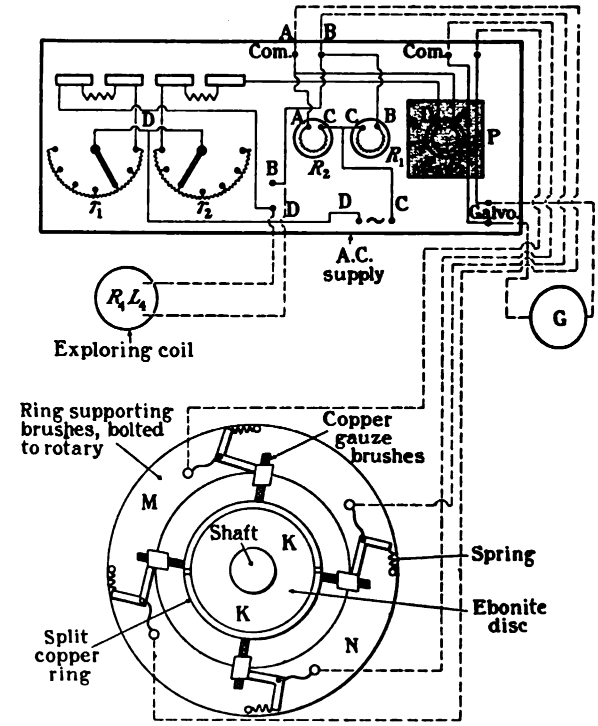

FIG. 2.

with the exception of L_4, R_4, were housed in a wooden box with terminals on the top, and connections were made to the rotary and commutator as shown. Originally the resistances AC and CB were made of manganin wire wound on a wooden bobbin and fixed in a wooden case. Each separate coil in the adjustable arms r_1 and r_2 had a resistance of approximately 0·01 ohm, and these were used both for balancing and for calibration purposes. Copper gauze brushes were used and these were fixed to an ebonite ring MN (see Fig. 2) which was screwed to an iron ring by means of bolts in slots, so allowing the brush gear to be rocked. The iron ring was fixed rigidly to the converter. The brush pressure was adjusted by means of small springs.

The apparatus as described above was fairly satisfactory, and readings could be obtained if great care was taken in adjusting the brush gear.

There were, however, many drawbacks, the chief of which were :—

(1) Gradual creep of the zero of the galvanometer, due to heating of the coils.
(2) Variation in the contact resistance of the variable resistances r_1 and r_2.
(3) Owing to lack of rigidity of the brushes, it was difficult to keep them in their correct relative position.

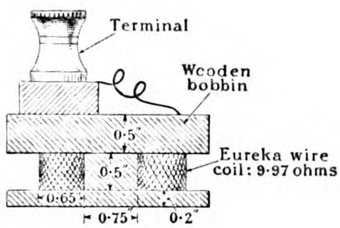

FIG. 2A.

(4) It was difficult to equalize the spring pressures of the brushes, and the pressures required were great enough to cause heating at the commutator surface and the development of thermo-E.M.F.'s.

(*b*) *Final form of apparatus.*—The above difficulties were overcome as follows :—

(1) Rewinding all the coils with No. 20 S.W.G. Eureka wire, each coil having a resistance of 9·97 ohms. The exploring coil is shown in section in Fig. 2A.

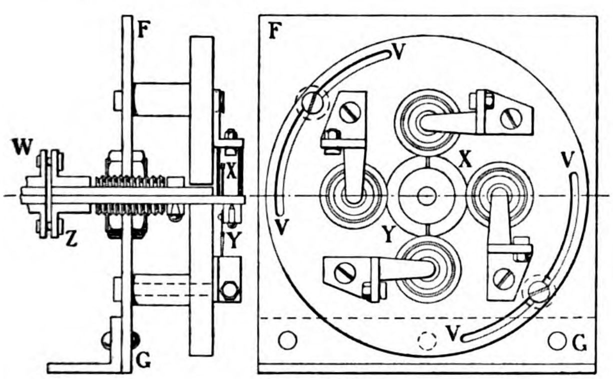

FIG. 3.

(2) Cutting out the regulating resistances and so doing away with the rubbing contacts. A small portion of r_1, however, was retained in order to obtain a balance, the connection to r_1 being made direct and not through a rubbing contact.
(3 and 4) were overcome by changing the design of the commutator.

The arrangement adopted is shown in Fig. 3. XY is the two-part commutator, mounted on an ebonite disc. The diameter of the commutator is considerably less than in the case of the one previously used, thus reducing the peripheral speed at the brush surface. The commutator, as before, is mounted on an extension of the shaft of the rotary converter, and is driven through a flexible coupling WZ. The brushes consisted of thin copper flexible discs.

It will be seen that the roller brushes * make contact with both faces of the commutator disc, and this, coupled with the fact that the roller brushes themselves had a great deal of "spring," ensured a very good surface contact, without the danger of any slipping between the revolving brush and the commutator disc. The roller brushes themselves were very light, and as their bearings were very thin steel spindles, no trouble was experienced with friction or heating at the roller brush bearings. These brushes ran for many hours faultlessly, it only being necessary occasionally to oil the bearings and contact surfaces and to make the contact between the brushes and the commutator disc greater as the brushes lost their "springiness."

It was only after a very considerable time that the brushes had to be replaced by new ones. No trouble

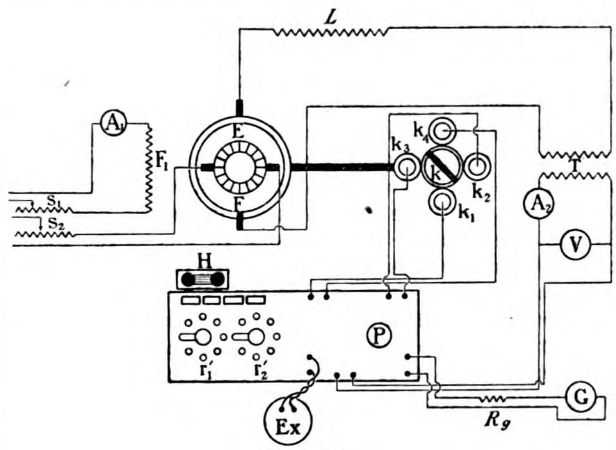

FIG. 4.

was caused due to thermo-E.M.F.'s. The mountings for the roller brushes were fixed to a large ebonite circular plate, which was attached to the main support GF by means of screws running in slots VV, so allowing the brushes to be rocked relative to the commutator. In this way it was possible to control the phase of the commutated current.

To enable the apparatus to be calibrated, a resistance of known magnitude and composed of Eureka wire was put in series with the coil DA. It was connected to the circuit through two mercury cups which were short-circuited by a thick copper strip when the resistance was removed (see H, Fig. 4).

The final diagram of connections is shown in Fig. 4. It will be seen that the supply from the converter to the bridge is made through a transformer, thus insulating the converter from the network.

A choking coil L is placed in series with the transformer in order to vary the value of the current.

The galvanometer previously used was a sensitive pointer unipivot type, but this was replaced by a reflecting galvanometer for most of the tests. In series with this galvanometer was placed a resistance of

* These brushes were kindly supplied by Mr. S. Evershed, and were similar to those used in the early form of ohmmeter.

400 ohms, and variations in the contact resistance of the roller brushes had consequently less effect on the galvanometer deflection than when the only resistance in the galvanometer circuit was the resistance of the galvanometer itself.

(c) *Method of using the apparatus.*—For most of the tests the speed of the 4-pole rotary converter was 1 500 r.p.m., so that the frequency was 50 cycles per second. Above this speed, vibration was considerable and difficulty was experienced with the brush contacts on the commutator. Some results were obtained, however, with a frequency as high as 66⅔ cycles per second. The effective change in resistance or inductance of the coil is dependent on the frequency of the supply—the lower the frequency, the smaller the effective change. When running at low speeds, therefore, the deflection of the galvanometer is smaller. In some later experiments it was found, however, that a speed to give about 35 cycles per second was quite sufficient to enable a large galvanometer deflection to be obtained, while at this speed the wear and tear on the brush gear is much less. It would appear, therefore, that a speed of 1 000 r.p.m. with a 4-pole machine would be the most suitable for ordinary testing.

In carrying out the tests the deflection of the galvanometer was brought near zero by means of the metal adjusting plate, and the exploring coil was then placed on the plate and the galvanometer deflection observed. In the later stages of the work it was never found necessary to alter the zero after it had once been set.

When working the apparatus there are usually only two positions in which the brushes on the commutator will be placed, i.e. the position corresponding to a measurement of effective resistance change, and the position corresponding to a measurement of effective inductance change. There are three methods available for determining these two brush positions. In the description of the apparatus it was stated that, in order to obtain a calibration, there was, in series with the coil DA, a resistance of known magnitude, the resistance being connected to two mercury cups, so that it could be put in circuit or taken out by short-circuiting the cups. Now if i_g * and i_g' represent the two components of the galvanometer current, i_g being the in-phase component, then it is shown in the Appendix that

$$i_g = K\delta R$$
$$i_g' = K'\delta L\omega$$

where δR and $\delta L\omega$ are the changes in effective resistance and inductance respectively and K and K are constants.

If the brushes are in such a position that i_g' is being commutated, there will be no current in the galvanometer circuit when the known resistance is put in or taken out of circuit. If the brushes are in the position where i_g is being commutated, the insertion of the known resistance will cause the galvanometer current to reach a maximum.

Actually, the position which gives no deflection for resistance-change was found as described above, and then the brush gear was rocked round 90 electrical degrees. It was found that in this position the insertion or removal of the known resistance gave the maximum deflection of the galvanometer.

* See Appendix.

As a further check, oscillograms were taken of the rectified wave of current when one pair of brushes was connected to the a.c. supply and the other side to the oscillograph, the brush gear being in the position corresponding to maximum resistance-change. It was found that in this position the commutator gave "complete" rectification.

The three methods of obtaining the positions of maximum deflection for resistance-change, therefore, give consistent results. From the oscillograms it would appear that any slight errors in obtaining the position in which it is desired to work would not have very great bearing on the accuracy of the results. This is borne out by the fact that the curve connecting the deflection of the galvanometer and the brush setting is very flat near the position of maximum effective resistance-change.* The actual values of the components of the galvanometer current in phase (i_g) and 90° out of phase (i_g') with the applied potential difference are given by

$$i_g = \frac{E\delta R}{4R_1R_g}$$

and

$$i_g' = \frac{EL_3\omega}{4R_1R_g}\left(\frac{\delta L\omega}{L_3\omega} - \frac{\delta R}{R_1}\right)$$

where the resistances of three of the arms of the bridge are each assumed to be equal to R_1 (the resistance of the fourth arm being $R_1 + \delta R$), the galvanometer resistance $= R_g$, and the applied P.D. $= E$.

The reactance of one inductive arm of the bridge is $L_3\omega$ and of the other inductive arm $L_3\omega + \delta L\omega$.

δR and $\delta L\omega$ are the changes in resistance and reactance of the exploring coil (the fourth arm) when a metal plate is brought near to it. For this apparatus it may be shown that $\delta L\omega/(L_3\omega)$ is about 100 times as great as $\delta R/R_1$, and, therefore, that i_g' is very nearly equal to $E\delta L\omega/(4R_1R_g)$.

(3) Some Experimental Results.

The apparatus was used to determine:—

(a) The change in effective resistance of the exploring coil due to metal plates of different thicknesses.
(b) The change in effective resistance of the exploring coil due to metal plates of different thicknesses at different distances from the exploring coil.
(c) The effect of change in frequency of the supply on the effective change in resistance of the coil when brought near to metal plates of different thickness.
(d) The change in effective inductance of the exploring coil due to metal plates of different thicknesses.

(a) *The change in effective resistance of the exploring coil due to metal plates of different thicknesses.*—This series of tests was carried out on copper, brass and zinc plates, varying in thickness from 0·0625 in. to 1 in., the frequency of supply to the bridge being

* The theory of the bridge network is given in an Appendix.

50 cycles per second, and the supply voltage being 4·3 volts. The distance of the base of the coil from the plates was 0·1 in. The results obtained are shown in Table 1.

TABLE 1.

Thickness	Deflection of galvanometer		
	Copper	Brass	Zinc
in.			
0·0625	10·1	—	3·
0·125	14·4	—	5·1
0·1875	15·3	6·05	7·1
0·25	15·0	7·0	8·5
0·375	13·6	7·8	9·8
0·625	12·4	8·0	9·7
1·0	11·7	7·8	9·1

In Fig. 5, which has been plotted from Table 1, is shown the relationship between the deflection of the galvanometer (which is proportional to the change in

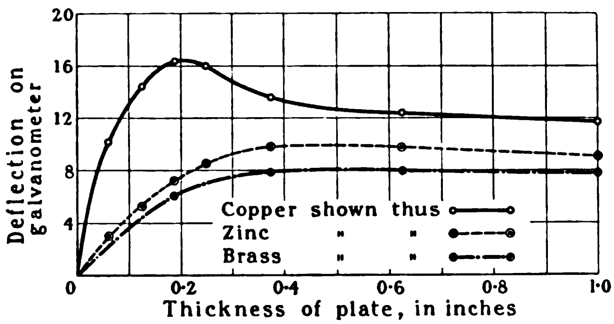

FIG. 5.

effective resistance of the exploring coil) and the thickness of the plate.

With the type of flux distribution set up by the coil shown in Fig. 2A, the equations of the curves in Fig. 5 are of the form

mercial copper and electrolytic copper plates, each plate being $\frac{1}{8}$ in. thick.

(*b*) *The change in effective resistance of the exploring coil due to metal plates of different thicknesses at different distances from the exploring coil.*—In Table 3 are shown

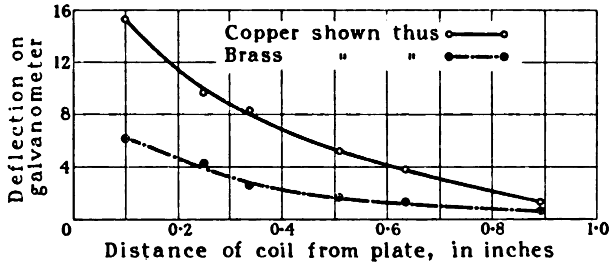

FIG. 6.

the experimentally determined values of the deflection of the galvanometer with the exploring coil at different distances from the plate. The tests were carried out at 50 cycles per second and with an applied voltage of 4·3.

The results are plotted in Fig. 6.

TABLE 2.

Deflection		
Electrolytic copper	Commercial copper	Zinc
31·5	16·3	11·2

(*c*) *The effect of change in frequency of the supply on the effective change in resistance of the coil when brought near to metal plates of different thicknesses.*—The experiments were carried out at three different frequencies, viz. 66⅔, 50, and 30 cycles per second. The distance of the coil from the plates was 0·218 in. The results are shown in Table 4, from which Fig. 7 has been plotted.

It will be seen that the deflections are approximately proportional to the square of the frequency.

$$\delta R = kL_3 w\left\{\frac{2\cosh\lambda Kh + \lambda\sinh\lambda Kh - 2\cos\nu Kh + \nu\sin\nu Kh}{\lambda^2(1+\frac{1}{4}\lambda^2)\cosh\lambda Kh + \lambda^3\sinh\lambda Kh + \nu^2(1-\frac{1}{4}\nu^2)\cos\nu Kh - \nu^3\sin\nu Kh}\right\}$$

where δR = change in effective resistance of the coil,
h = thickness of plate,

and where λ, ν, K and k are constants depending on the specific resistance of the plate, the frequency of the supply, the distance of the coil from the plate, and the nature of the flux distribution due to the coil. The curves rise very rapidly at first, reach a maximum, and then approach an asymptote, the change in effective resistance of the coil becoming independent of the thickness of the metal. The difference in deflection, however, with very thick plates of widely different specific resistances is relatively small. With thin plates the difference between the deflections observed with materials of different specific resistances is much greater. In Table 2 are shown results obtained with zinc, com-

(*d*) *The change in effective inductance of the exploring*

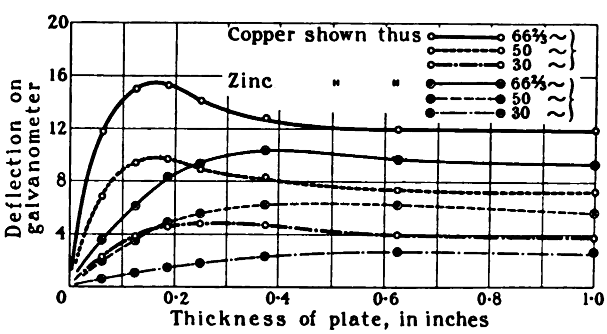

FIG. 7.

coil due to metal plates of different thicknesses.—In Table 5 are shown the experimentally determined

values of the deflection of the galvanometer, due to change of inductance, when the exploring coil was

TABLE 3.

Distance of coil from plate	Deflection of galvanometer	
	0·1875 in. plate copper	0·1875 in. brass
in.		
0·1	15·3	6·05
0·25	9·65	4·2
0·339	8·3	2·57
0·507	5·2	1·65
0·635	3·85	1·35
0·892	1·35	0·75

placed on copper and zinc plates of different thicknesses. The values are plotted in Fig. 8. The brushes were in

TABLE 4.

Thickness of plate	Deflection					
	Copper			Zinc		
	$66\frac{2}{3}$ cycles per sec.	50 cycles per sec.	30 cycles per sec.	$66\frac{2}{3}$ cycles per sec.	50 cycles per sec.	30 cycles per sec.
in.						
0·0625	11·85	7·0	2·2	3·6	2·05	0·55
0·125	15·05	9·45	3·8	6·1	3·45	0·9
0·1875	15·3	9·65	4·5	8·4	4·7	1·4
0·25	14·15	8·9	4·7	9·2	5·5	1·75
0·375	12·8	8·3	4·65	10·3	6·2	2·35
0·625	12·0	7·4	4·05	9·7	6·15	2·7
1·0	12·0	7·35	3·9	9·3	5·7	2·7

the " out of phase " position. The distance of the coil from the plate = 0·1 in.

TABLE 5.

Thickness	Deflection	
	Copper	Zinc
in.		
0·0625	4·1	1·2
0·125	9·7	2·1
0·1875	12·9	3·15
0·25	14·4	4·45
0·375	16·4	6·0
0·625	17·7	7·6
1·0	17·4	8·2

It can be shown mathematically that the shapes of these curves are given by

$$\delta L\omega = -L_3 \omega k \left\{ \frac{k \cosh \lambda K h + \nu \sinh \lambda K h - k \cos \nu K h - \lambda \sin \nu K h}{\lambda^2 (1 + \frac{1}{4}\lambda^2) \cosh \lambda K h + \lambda^3 \sinh \lambda K h + \nu^2 (1 - \frac{1}{4}\nu^2) \cos \nu K h - \nu^3 \sin \nu K h} \right\}$$

where $\delta L\omega$ is the change in inductance, h is the thickness of plate, and λ, ν, K and k are constants depending on the specific resistance, frequency, distance of the coil from the plate and the nature of the flux distribution due to the coil.

These curves do not reach a maximum in the same way as the resistance curves, but rise continuously to an asymptotic value for very thick plates. The ratio between the deflections for different materials with very thick plates is much greater than when observing changes in effective resistance and is approximately proportional to the square root of the specific conductivity.

The measurement of inductance-change, therefore, is suitable for comparing the conductivity of non-magnetic metals, and, provided the plate is more than ½ in. thick, the deflection is almost independent of the thickness of the plate.

With the brushes in the out-of-phase position, the

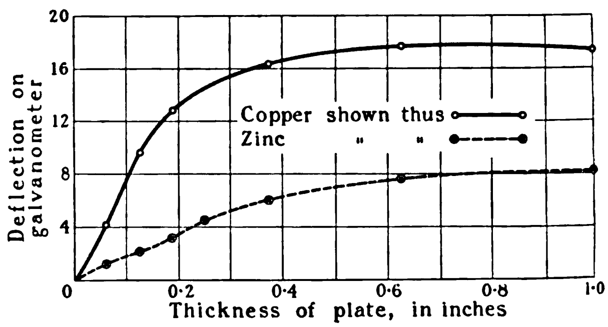

FIG. 8.

apparatus provides a quick and easy method of comparing the conductivities of metal plates. It may, for example, be used for testing whether copper sheet or brass sheet is of uniform quality, and, provided the thickness of the plates is known, it will enable the specific conductivities to be compared directly, but if plates of different thicknesses are to be compared, provided the thickness is less than ½ in., it will be necessary to use a correction factor if accurate results are to be obtained. If a plate of material has a crack or other defect in the surface, this is at once indicated if the coil is moved over the surface of the plate, by a reduction in the deflection of the indicating instrument. Copper plates have been cracked and put together again so as to be practically continuous, but the presence of the cracks is always shown, the deflection of the instrument falling almost to zero when the area containing the crack is passed over. If the apparatus is to be used for testing magnetic materials, it will be necessary to use it in the "in phase" position, otherwise the change of inductance due to the presence of the magnetic material will be observed. If, however, the coil is brought near to an iron plate, eddy currents which change its effective resistance are induced in it, and the presence of a crack in the surface is at once shown in the deflection of the galvanometer.

Another possible application of the apparatus is in testing the electrical conductivity of welded rails. If the electrical circuit between the rails is sound, this would be indicated by a steady deflection of the galvanometer if a suitably shaped coil is passed over the joint, whereas if any crack is present it is indicated by a change in the deflection of the instrument.

APPENDIX.

Theory of the Bridge Network.

CB and CA are the two non-inductive coils of resistance R_1 and R_2, forming the "proportional arms." BD and AD are the two "ratio arms," whose resist-

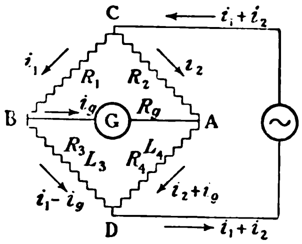

Fig. 9.

ances and inductances are R_3, L_3, and R_4, L_4, respectively. In Fig. 9 are shown the instantaneous values of the currents.

If current $i_1 = i_1 + ji_1'$ and current $i_2 = i_2 + ji_2'$

then P.D. from C to B $= R_1(i_1 + ji_1')$

and P.D. from C to A $= R_2(i_2 + ji_2')$

$$\therefore\ i_g = \frac{R_1(i_1 + ji') - R_2(i_2 + ji_2')}{R_g}$$

(*Continued at top of next column.*)

where R_g = total resistance in galvanometer circuit, or

$$i_g = \frac{R_1 i_1 - R_2 i_2}{R_g} + j\left\{\frac{(R_1 i_1' - R_2 i_2')}{R_g}\right\}$$

If $i_g = i_g + ji_g'$, then

$$i_g = \frac{R_1 i_1 - R_2 i_2}{R_g} \quad \text{and} \quad i_g' = \frac{R_1 i_1' - R_2 i_2'}{R_g}$$

As $R_1 = R_2$

$$i_g = \frac{R_1}{R_g}(i_1 - i_2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and

$$i_g' = \frac{R_1}{R_g}(i_1' - i_2') \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

P.D. between B and D

$$= \{(i_1 - i_g) + j(i_1' - i_g')\}\{R_3 + jL_3\omega\}$$

P.D. between A and D

$$= \{(i_2 + i_g) + j(i_2' = i_g')\}\{R_4 + jL_4\omega\}$$

Now P.D. in CBD = P.D. in CAD

$$\therefore\ R_1(i_1 + ji_1') + \{(i_1 - i_g) + j(i_1' - i_g')\}\{R_3 + jL_3\omega\}$$
$$= R_2(i_2 + ji_2') + \{(i_2 + i_g) + j(i_2' + i_g')\}\{R_4 + jL_4\omega\}$$
$$= E + jE'$$

where $E + jE'$ is the applied P.D.

Equating real and unreal parts, taking $E' = 0$, then

$$(R_1 + R_3)i_1' + L_3\omega i_1 - R_3 i_g' - L_3\omega i_g = 0 \quad . \quad (3)$$
$$(R_1 + R_3)i_1 - L_3\omega i_1' - R_3 i_g + L_3\omega i_g' = E \quad . \quad (4)$$
$$L_4\omega i_2 + (R_2 + R_4)i_2' + L_4\omega i_g + R_4 i_g' = 0 \quad . \quad (5)$$
$$(R_2 + R_4)i_2 - L_4\omega i_2' + R_4 i_g - L_4\omega i_g' = E \quad . \quad (6)$$

Eliminating i_1, i_2, i_1', i_2' from equations (1), (2), (3), (4), (5) and (6), then

$$i_g\left[1 - \frac{R_1\{R_3^2 + R_1R_3 + L_3\omega^2\}}{R_g\{(R_1 + R_3)^2 + L_3\omega^2\}} - \frac{R_1\{R_4^2 + R_2R_4 + L_4\omega^2\}}{R_g\{(R_2 + R_4)^2 + L_4\omega^2\}}\right]$$
$$= \frac{ER_1}{R_g}\left[\frac{R_1 + R_3}{\{(R_1 + R_3)^2 + L_3\omega^2\}} - \frac{R_2 + R_4}{\{(R_2 + R_4)^2 + L_4\omega^2\}}\right] - i_g'\left[\frac{R_1^2 L_3\omega}{\{(R_1 + R_3)^2 + L_3\omega^2\}R_g} + \frac{R_1R_2L_4\omega}{R_g\{(R_2 + R_4)^2 + L_4\omega^2\}}\right]$$

and

$$i_g'\left[1 - \frac{R_1\{R_3^2 + R_1R_3 + L_3\omega^2\}}{R_g\{(R_1 + R_3)^2 + L_3\omega^2\}} - \frac{R_1\{R_4^2 + R_2R_4 + L_4\omega^2\}}{R_g\{(R_2 + R_4)^2 + L_4\omega^2\}}\right]$$
$$= \frac{ER_1}{R_g}\left[\frac{L_4\omega}{\{(R_2 + R_4)^2 + L_4\omega^2\}} - \frac{L_3\omega}{\{(R_1 + R_3)^2 + L_3\omega^2\}}\right] + i_g\left[\frac{R_1^2 L_3\omega}{R_g\{(R_1 + R_3)^2 + L_3\omega^2\}} + \frac{R_1R_2L_4\omega}{R_g\{(R_2 + R_4)^2 + L_4\omega^2\}}\right]$$

Now $R_1 = R_2$.

Put $R_4 = R_3 + \delta R$ and $L_4\omega = L_3\omega + \delta L\omega$,

and arrange :—

$$i_g\left[1 - \frac{R_1\{R_3^2 + R_1R_3 + L_3\omega^2\}}{R_g\{(R_1 + R_3)^2 + L_3\omega^2\}}\left\{1 + \frac{1 + [\delta R(R_1 + 2R_3)/(R_3^2 + R_1R_3 + L_3\omega^2)] + [2L_3\omega\delta L\omega/(R_3^2 + R_1R_3 + L_3\omega^2)]}{1 + [\{2\delta R(R_1 + R_3)\}/\{(R_1 + R_3)^2 + L_3\omega^2\}] + [(2L_3\omega\delta L\omega)/\{(R_1 + R_3)^2 + L_3\omega^2\}]}\right\}\right]$$
$$= \frac{ER_1(R_1 + R_3)}{R_g\{(R_1 + R_3)^2 + L_3\omega^2\}}\left[1 - \frac{1 + \{\delta R/(R_1 + R_3)\}}{1 + [2\delta R(R_1 + R_3)/\{(R_1 + R_3)^2 + L_3\omega^2\}] + [2L_3\omega\delta L\omega/\{(R_1 + R_3)^2 + L_3\omega^2\}]}\right]$$
$$- \frac{i_g' R_1^2 L_3\omega}{R_g\{(R_1 + R_3)^2 + L_3\omega^2\}}\left[1 + \frac{1 + \{\delta L\omega/L_3\omega\}}{[1 + 2\delta R(R_1 + R_3)/\{(R_1 + R_3)^2 + L_3\omega^2\}] + [2L_3\omega\delta L\omega/\{(R_1 + R_3)^2 + L_3\omega^2\}]}\right]$$

or

$$i_g(R_gM - 2R_1N) = ER_1(R_1 + R_3)\left[\frac{2\delta R(R_1 + R_3)}{M} + \frac{2L_3\omega\delta L\omega}{M} - \frac{\delta R}{(R_1 + R_3)}\right] - 2i_g' R_1^2 L_3\omega$$

if δR and $\delta L\omega$ are very small compared with R_1 and $L_3\omega$ respectively, where

$$M = (R_1 + R_3)^2 + L_3\omega^2 \text{ and } N = R_3^2 + R_1R_3 + L_3\omega^2$$

We have, similarly, $i'_g(R_gM - 2R_1N) = 2i_gR_1^2L_3\omega - ER_1L_3\omega\left[\frac{2\delta R(R_1 + R_3)}{M} + \frac{2L_3\omega\delta L\omega}{M} - \frac{\delta L\omega}{L_3\omega}\right]$

From these equations i_g can be obtained :—

$$i_g = \frac{ER_1}{R_gM}\left[(R_1 + R_3)\left\{\frac{2\delta R(R_1 + R_3)}{\{(R_1 + R_3)^2 + L_3\omega^2\}} + \frac{2L_3\omega\delta L\omega}{\{(R_1 + R_3)^2 + L_3\omega^2\}} - \frac{\delta R}{R_1 + R_3}\right\}\right] = \frac{ER_1\delta R}{R_g(R_1 + R_3)^2}$$

which shows that if the values of R_1, R_2, R_3 and R_4 are large compared with $L_3\omega$, the current in the galvanometer circuit, when the brushes are in the "in phase" position, depends only on the effective change in resistance of the coil.

In the case when $R_1 = R_3$, $i_g = \dfrac{E\delta R}{4R_1R_g}$.

Taking the actual values used in the experiments, i.e. $E = 4\cdot3$, $R_1 = 10$ ohms, $R_g = 440$ ohms,* then $i_{g\,max.} = 0\cdot244\ \delta R \times 10^{-3}$ amp.

When the calibrating resistance, which has a resistance of $0\cdot0022$ ohm and is in series with R_1, is inserted, the calculated maximum value of the galvanometer current is $0\cdot537 \times 10^{-6}$ amp.

The observed galvanometer current was $0\cdot396 \times 10^{-6}$ amp. In order to obtain agreement between the calculated R.M.S. value and the observed value of the galvanometer current, a form factor of $1\cdot36$ must be used. This form factor is obtained because, owing to the short-circuiting of the two halves of the commutator by the brushes, each half wave of the rectified current is not sinusoidal.

As a further check on the theory, the two 10-ohm ratio arm coils were replaced by two coils, each having a resistance of 1 ohm.

Again taking the actual value in the experiment, i.e. $E = 3\cdot8$ volts, $R_1 = 10$ ohms, $R_3 = 1$ ohm and $R_g = 150$ ohms,* and substituting in

$$i_g = \frac{ER_1\delta R}{R_g(R_1 + R_3)^2 \times 1\cdot36}$$

then $i_g = 3\cdot39 \times 10^{-6}$ amp.

The observed current was $3\cdot3 \times 10^{-6}$ amp.

In the same way

$$i'_g = \frac{EL_3\omega}{4R_1R_g}\left\{\frac{\delta L\omega}{L_3\omega} - \frac{\delta R}{R_1}\right\}$$

if $R_1 = R_3$ and $R_1 > L_3\omega$.

With the brushes in the "out of phase" position there is no galvanometer current when the calibrating resistance is inserted, which shows that the galvanometer current is independent of resistance change with the brushes in the out-of-phase position.

$$\therefore\ \delta R/R_1 < \delta L\omega/(L_3\omega)\ \dagger$$

$$\therefore\ i'_g = \frac{E\delta L\omega}{4R_1R_g} \text{ very nearly.}$$

When the coils R_1 and R_2 are equal in resistance but are different from R_3 and R_4, the value of i'_g is given by

$$i'_g = \frac{ER_1\delta L\omega}{R_g(R_1 + R_3)^2}.$$

* This value of R takes account of the brush contact resistance. This was measured and found to vary from 10 ohms when the brushes were new and well lubricated, to about 40 ohms when the springiness and trim of the brushes had worn off.

As an approximation, 25 ohms was added to the known galvanometer circuit resistance of 415 ohms.

* A smaller resistance was used in the galvanometer circuit with this coil. The 150 ohms takes account of brush contact resistance.

† This can be shown by a mathematical investigation of the eddy currents induced in the metal plates. In this case it was found that $\delta R/(\delta L\omega)$ was approximately 1/100.

THE GENERATION OF VERY INTENSE MAGNETIC FIELDS.*

By T. F. WALL, D.Sc., D. Eng., Member.

(*Paper first received* 27*th October*, 1925, *and in final form* 26*th May*, 1926.)

SUMMARY.

The paper describes a method for generating magnetic fields of the order of magnitude of 1 million gauss, and for impressing such fields on a specimen of magnetic material at regular intervals, with a view to ascertaining whether any disturbance of the electronic orbits could be obtained of sufficient magnitude to produce a marked effect on the magnetization curve of the specimen.

An account is given of the means used for measuring the magnitude and frequency of the heavy transient currents to which the intense magnetic fields are due.

The influence of the dimensions of the solenoid through which the transient currents flow is considered as determining the intensity of the magnetic field produced.

A comparison is given of the calculated and measured values of the transient currents for three different solenoids. It is found that, whilst the calculated values agree well with the measured values for solenoids with a relatively small number of turns of thick wire, there is an appreciable discrepancy in the case of a solenoid with a large number of turns of thin wire. An attempt is made to explain this discrepancy as due to the condenser effect of the contact E.M.F. between the copper wire and the oil-soaked cotton insulation which is in contact with the wire.

INTRODUCTION.

In the reply † to the discussion on a recent paper, Mr. S. Evershed made some interesting suggestions as to the possibility of a disturbance of the electronic orbits within the atoms of a magnetic substance being effected by impressing on them a very intense magnetic field.

The following investigation ‡ was undertaken primarily for the purpose of generating very intense magnetic fields and impressing these fields on a magnetic substance with a view to disturbing the electronic orbits within the atoms.

Now calculation shows § that even if the impressed magnetic field is of the order of 1 million gauss, the corresponding change in the magnetic moment of a revolving electron will only be of the order of 0·1 per cent.

It appeared to the author, however, that there might be a reasonable possibility of obtaining an appreciable disturbance of the electronic orbits if the impressed magnetic fields were to be repeatedly applied. Taking, as an analogous case, the breakdown of the structure of materials by the repeated application of stresses of a magnitude such that a single application would not produce any noticeable effect on the strength, it seems reasonable to suppose that, in an analogous manner, a repeated application of an impressed magnetic field on the electronic orbits would produce a cumulative effect so that eventually a marked change in the magnetic properties of the material would be observed—in particular, a marked change in the magnetization curve of the material.

Although this case of the breakdown of the mechanical structure by repeated application of relatively weak stresses is only mentioned here as an analogy, the author is of the opinion that there is nevertheless a very real relationship between the two cases, the phenomenon of coherence and other mechanical properties of a material being probably, in their ultimate aspect, electromagnetic phenomena.

The problem therefore resolved itself into the following parts :—

(1) The generation of very intense magnetic fields and the impression of these fields on a sample of magnetic material.

(2) The repeated application of these intense magnetic fields by means of a suitable automatically-operated device.

(3) A comparison of the magnetization curve of the sample after the repeated application of the intense magnetic fields, with the magnetization curve of the sample before being subjected to these intense fields.

In the present paper, attention is confined mainly to the problem of generating the very intense magnetic fields and the measurement of the condenser discharge currents to which these fields are due.

Section 1. DESCRIPTION OF THE METHOD AND APPARATUS USED FOR THE GENERATION OF VERY INTENSE MAGNETIC FIELDS.

The basic idea of the method for producing very intense magnetic fields is this : Since the heat generated by a current of i amperes flowing for a time of t seconds in a conductor of resistance R ohms is

$$i^2Rt \text{ joules,}$$

it follows that if the time t be sufficiently small it is possible to pass an indefinitely large current through the conductor without fusing it.

Now if a solenoid is uniformly wound with w turns per cm length, the intensity of the magnetic field generated at the central part within the core is

$$H = k\frac{4\pi}{10}iw \text{ gauss,}$$

where i is the current in amperes and k is a correction coefficient depending on the dimensions of the solenoid.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1920, vol. 58, p. 832.

‡ See also *Nature*, 1924, vol. 113, p. 568.

§ S. EVERSHED, *loc. cit.*; also "Dictionary of Applied Physics," vol. 2, p. 514.

If the solenoid is of very great length as compared with its diameter, the value of k may be taken to be unity.*

If, therefore, the magnitude of the current i is made sufficiently large, the intensity of the magnetic field may be increased indefinitely. Suppose, for example, that a long solenoid is wound with 40 turns per cm length and it is required to obtain a magnetic field of intensity 10^6 gauss at the central part within the core of the solenoid. The current necessary to produce this field will be

$$i = \frac{10^7}{4\pi w} = 19\,900 \text{ amperes.}$$

If the solenoid is wound with, say, No. 16 S.W.G. wire, the normal current-carrying capacity of which is about 13 amperes, it is clear that the current of about 20 000 amperes can only be permitted to flow for a very small fraction of a second if the solenoid winding is not to be burned out.

In order, therefore, that the two essential requirements should be fulfilled, viz.

(i) that very large currents should be generated in the solenoid winding; and

(ii) that these currents should only be allowed to flow for a very small fraction of a second,

the author decided to use the oscillatory discharge of electrostatic condensers of high capacity and charged to a high potential difference.†

The condensers used were of the paper-insulated, oil-immersed power type as supplied by Messrs. British Insulated and Helsby Cables, Ltd. These condensers were supplied in units of a nominal value of 50 μF each, and each unit was capable of withstanding a charging pressure of 2 000 volts (d.c.).

For the tests described in the following, 28 of these units were available, the total capacity of the units when connected in parallel being 1 366 μF.

The condensers were charged by means of a small d.c. generator as built for wireless telegraph purposes. This generator develops an E.M.F. of about 1 200 volts and is capable of supplying a current of about 0·02 ampere. In series with this generator were connected a number of small accumulators as used for wireless telegraph work, so that the total available d.c. pressure for charging the condensers was about 2 000 volts.

The d.c. supply so provided was connected in series with a high resistance of the value of about 0·25 megohm, so that when the discharged condensers were connected to the supply there would not be any heavy rush of current from the generator and accumulators.

The condensers required about 3 to 4 minutes to become fully charged under these conditions.

After having become fully charged, the condensers were then connected directly to the solenoid winding within the core of which the intense magnetic fields were to be generated, care being taken to keep the resistance and inductance of the leads from the condensers to the solenoid as small as practicable.

The solenoid was immersed in a bath of transformer oil which served the double purpose of maintaining a high value for the insulation resistance between neighbouring turns of the winding, and for effectively cooling the solenoid winding after the passage of the very heavy discharge currents from the condensers. As these currents reached momentary values of many thousands of amperes, it was essential to ensure that the heat generated in the solenoid winding should be conducted away as quickly and effectively as possible.

The measurement of the magnitudes of the very heavy currents generated when the condensers are discharged through the solenoid winding has been a problem of some difficulty. The method employed is the use of the Duddell high-frequency oscillograph and "falling plate" camera.

In order to ensure that the photographic plate shall pass across the exposure slit at precisely the moment at which the condenser discharge is taking place, an electromagnetic release device for the plate is employed. The electromagnet circuit is closed by means of a contact fixed to the arm of the switch which closes the discharge circuit of the condensers. By suitably adjusting the position of the contact it is possible so to arrange matters that the condenser discharge takes place just as the plate is passing across the exposure slit.

The setting of the contact maker for the plate-release electromagnet proved to be extremely sensitive, and a very slight change in the friction of the plate in the guides was sufficient to upset it completely so that the condenser discharge was completed either before or after the plate had passed across the exposure slit. It was eventually found to be necessary to provide means for eliminating the disturbing effect of slight errors or alterations in the setting of the contact maker. For this purpose a special plate frame was made which would carry three plates, thus forming, in effect, one continuous plate about 18 in. long. In this way it has been found possible to ensure that the condenser discharge takes place while at least some portion of this composite plate is crossing the exposure slit.

The frequency of the oscillatory current produced by the condenser discharge is measured by connecting one strip of the oscillograph to a source of sinusoidal alternating current of known frequency, e.g. the town supply mains, whilst the other strip of the oscillograph is in circuit with the discharge current of the condenser.

Fig. 1 shows diagrammatically the general arrangement of the connections. Reference to this diagram shows that when the switch lever E is over on the left-hand side and the switch U is closed, the condensers are all connected in parallel to the high-voltage supply system C. The P.D. at the condenser terminals is measured by the Kelvin electrostatic voltmeter O. When the switch lever E moves over to the right-hand side, contact is first made in the two mercury cups J, the result of this being to connect the two condenser sets B in series. The actual closing of the condenser discharge circuit is effected by contact in the large mercury cup H.

* The actual value of the correction coefficient is

$$k = \frac{2b}{4d} \log_e \left[\frac{(a+d) + \sqrt{[(a+d)^2 + b^2]}}{(a-d) + \sqrt{[(a-d)^2 + b^2]}} \right]$$

where a is the mean radius in cm of the solenoid winding,
$2d$ is the radial depth in cm of the solenoid winding,
$2b$ is the length in cm of the solenoid winding.

See A. GRAY: "Absolute Measurements in Electricity and Magnetism," 2nd Edition, page 216.

† P. KAPITZA has described (*Proceedings of the Royal Society*, A, 1924, vol. 105, p. 691) a method of producing intense magnetic fields by means of the discharge of accumulators.

The resistance Q is provided as a safety discharge resistance so that, if desired, the condensers may be short-circuited when necessary and thus rendered safe for handling.

The condenser discharge current through the solenoid passes through the standard resistance R. The value of this resistance was 0·002 ohm for many of the tests, whilst for the remainder of the tests the value was 0·001 ohm.

from the self-induction of the resistance itself. That is to say, the P.D. across the terminals of the resistance will not be merely that due to the IR drop, but there may be a relatively high voltage induced by the self-induction and therefore proportional to the rate of change dI/dt, and this voltage of self-induction may be relatively large, notwithstanding the fact that the resistance is a conductor in the form of a straight rod.

In order to obviate any trouble due to self-induction

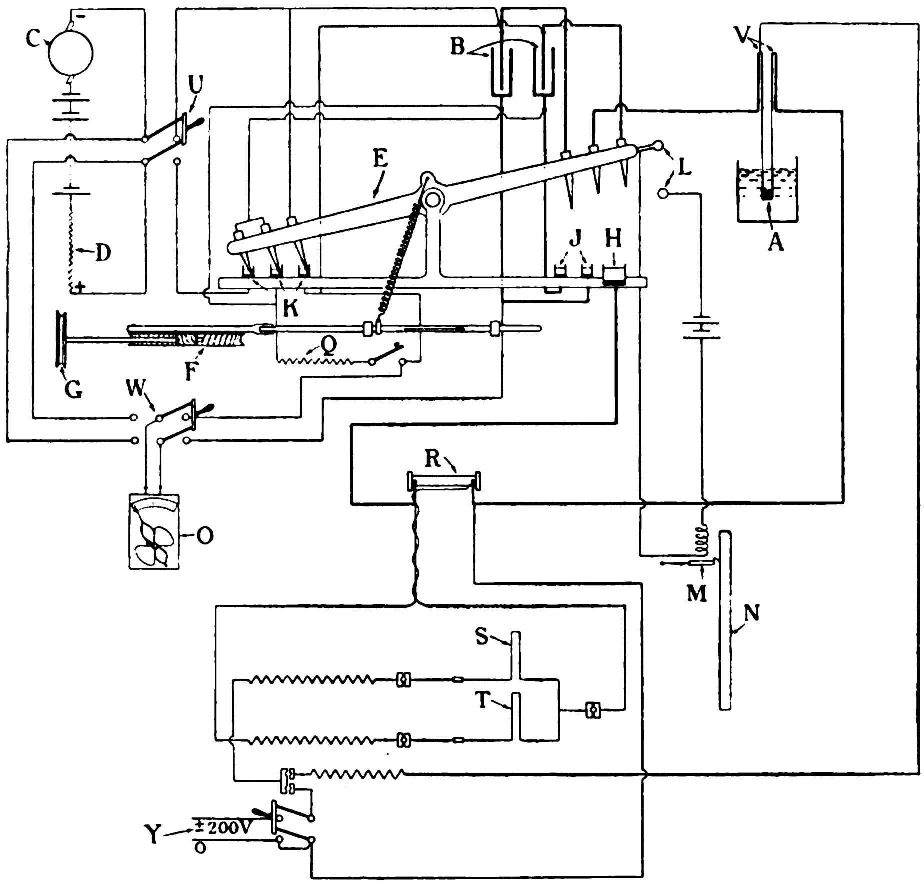

FIG. 1.

A = Solenoid exciting intense magnetic field.
B = Condensers.
C = High-voltage d.c. generator in series with high-voltage battery.
D = Buffer resistance.
E = Motor-driven oscillating switch.
F = Worm gearing driving oscillating switch E.
G = Belt pulley driving worm gearing F.
H = Main mercury contact for condenser discharge circuit.
J = Mercury contact cups for connecting condensers in series for discharging.
K = Mercury contact cups for charging condensers.
L = Contact for actuating electromagnet M.
M = Electromagnet operating photographic plate release.
N = Photographic plate slide for oscillograph.
O = Kelvin electrostatic voltmeter for measuring condenser charging voltage.
Q = Auxiliary safety resistance for discharging condensers.
R = Oscillograph standard shunt for measuring condenser discharge current.
S = P.D. strip of oscillograph.
T = Current strip of oscillograph.
U = Switch for high-voltage supply.
V = Non-inductive leads to solenoid A.
W = Switch for electrostatic voltmeter.
Y = A.C. supply (50 cycles) for calibrating oscillograph.

In view of the very large currents to be dealt with, the measurement of the magnitudes of these currents by means of the oscillograph required special precautions to eliminate mutual induction effects between the solenoid leads and the leads to the oscillograph. The current was measured by connecting one strip of the oscillograph as a shunt to the standard resistance R. The form of this resistance is therefore of considerable importance. For instance, if this resistance is of small ohmic value and if the length is large, trouble may arise

effects, the length of the resistance R was kept small, viz. 5 in. Further, instead of bringing the oscillograph leads from the standard resistance R at right angles, one of the leads was arranged to pass along the resistance and close to it, being then twisted round the other tapping lead as shown in Fig. 1. In this way, self-induction effects in the resistance R were eliminated and the P.D. supplied to the oscillograph strip circuit was strictly proportional to the current in the circuit of the solenoid A.

A special precaution was also taken in regard to the P.D. oscillograph connections for measuring the P.D. wave across the coil. For this purpose non-inductive double strips V (Fig. 1) were connected directly to the solenoid terminals, the length of each double strip being about 2 in. Tappings were taken from the top of these double strips, one of these tappings being shown in Fig. 1. In this way any mutual induction effects in the P.D. leads due to the heavy currents in the circuit could be eliminated. It was found, however, that mutual induction effects in the P.D. circuit of the oscillograph circuit were insignificantly small even without this special precaution.

The slide frame for the photographic plates is shown at N and the electromagnet for the plate release at M. The circuit of this electromagnet is closed as the switch lever E moves over to the right-hand side.

The a.c. wave of 50 frequency for measuring the frequency of the oscillatory discharge currents in the solenoid A, and also for calibrating the oscillograph, is obtained from the supply mains shown at Y.

The calibration of the oscillograph is performed by connecting the two strips in series with each other through a known resistance and supplying the circuit

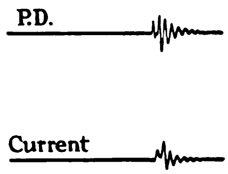

FIG. 2.

from the a.c. source Y, the P.D. being accurately measured.

For each condition of condenser discharge, two sets of oscillograms were usually taken, viz.

(i) One set giving the waves of the P.D. and the current in the solenoid.

(ii) One set giving the wave of the condenser discharge current and a sinusoidal wave of known frequency.

The second of these two sets of oscillograms provides the scale for measuring the frequency of the condenser discharge current.

As previously mentioned, a disturbing factor in the resistance of the discharge circuit is the mercury cup contact H through which the actual closing of the discharge circuit is effected. What appears to happen is the following: Before the switch blade of the large cup contact H (Fig. 1) actually touches the mercury surface, a spark passes, the mercury is partly vaporized and its surface set in violent motion. The contact resistance of the mercury is thus a somewhat uncertain quantity. Further, the mercury surface may oscillate so violently that the contact may be broken at some time during the discharge. This appears to be the case in the oscillograms such as those given in Figs. 4 (*a*) and 5 (*b*), in which there is an actual cessation of the current for a short time, after which the discharge is resumed. Moreover, even though the discharge does not start with a spark from the switch blade to the surface of the mercury, the surface may be set oscillating by the mechanical effect of the blade striking through the surface.

In order to minimize these effects at the surface of the mercury, the contact cup H (Fig. 1) through which the discharge circuit is completed is made very large, viz. about 6 inches in diameter and about 8 in. deep. The mercury is about 1 in. deep and the cup is filled to the top with oil. In this way the spark was largely suppressed and the oscillations at the surface of the mercury were largely wiped out.

For the purpose of examining a little further the effect of the mercury contact on the flow of current in the circuit, an oscillogram was taken for the condenser discharge current when the condensers were charged up to a very low voltage, so that any disturbance due to sparking at the contact should be insignificant. For this test the condensers were arranged in two sets in parallel, the capacity of the two sets being $243 \cdot 3\ \mu$F and $243 \cdot 2\ \mu$F respectively. These two sets were charged to a P.D. of 10 volts in parallel and connected in series for the discharge.

In Fig. 2 are shown oscillograms of the P.D. and current waves respectively, for these conditions of condenser discharge. An inspection of these oscillograms shows that in this instance there is a marked disturbance at the commencement of the discharge, after which the oscillations become normal.

As previously stated, the system of connections to the mercury cups shown in Fig. 1 is such that, whilst the condensers are all connected in parallel for charging (that is, the rocking-lever switch arm E is in contact with the left-hand set of mercury cups), before the discharge takes place the condensers are connected in two sets in series. By connecting the condensers in series in this way for discharging it is possible to obtain (within limits) much higher values for the discharge currents than if all the condensers remained in parallel at discharging.

For example, take the following values for the constants of the circuit, viz. inductance $L = 50/10^6$ henry, and resistance $R = 0 \cdot 15$ ohm. Suppose the total capacity of the condensers available is 1 360 μF and that these condensers will stand charging at 2 000 volts. If the condensers are all charged up to 2 000 volts in parallel and if they are kept in parallel at discharge, calculation shows that the magnitude of the first peak of the oscillatory discharge current will be 5 800 amperes and the frequency of the oscillatory current will be 563 cycles per second.

If, however, the condensers after being all charged in parallel to 2 000 volts are then arranged in two equal sets connected in series, the magnitude of the first peak of the oscillatory discharge current will be 7 780 amperes and the frequency 1 200 cycles per second.

It is seen, therefore, that the discharge current in the solenoid reaches a maximum value which is 34 per cent greater when the condensers are discharged in two equal sets in series than when the discharge takes place with all the condensers connected in parallel.

By connecting the condensers in, say, 4 equal sets in series when discharging, the maximum value of the discharge current may be still further increased.

Section 2. COMPARISON OF THE MEASURED VALUES OF THE CONDENSER DISCHARGE CURRENTS AND FREQUENCIES WITH THE VALUES CALCULATED FROM THE CONSTANTS OF THE CIRCUIT.

In order to provide a check on the method described in Section 1 for measuring the magnitudes of the transient currents obtained when the condensers are discharged through the solenoid, and also to ascertain whether any new phenomena were becoming evident due to the high values of the currents obtained, three special solenoids were wound and their dimensions accurately determined.

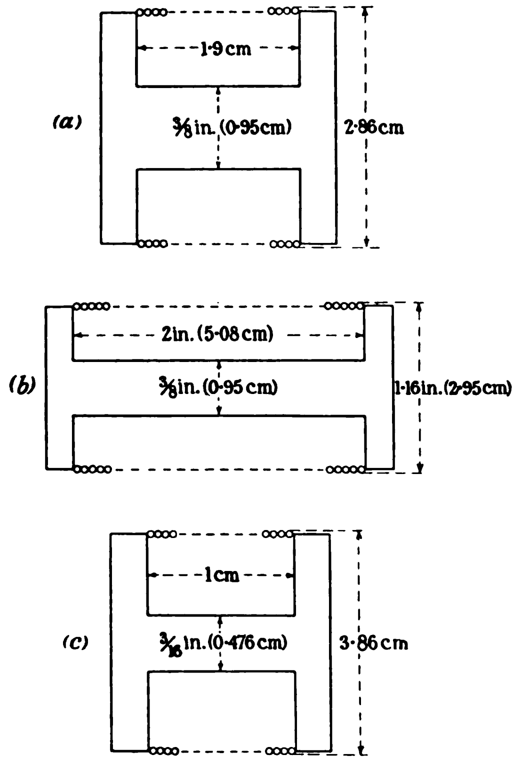

FIG. 3.

	Solenoid		
	A (a)	B (b)	C (c)
No. of turns per layer	9·6	26·5	10
No. of layers	5	5	18
Total no. of turns	48	132·5	180
Size of wire (S.W.G.)	No. 16	No. 16	No. 22

The results obtained in these tests, especially those referring to the solenoid described in the following as solenoid C, do in fact indicate that a peculiar phenomenon is coming to light. This is dealt with in the discussion of the results obtained with solenoid C.

Each of these solenoids was wound on an ebonite bobbin in order to eliminate any extraneous disturbing effects which might have occurred if the bobbin had been of metal.

The three solenoids are shown in section in Fig. 3, the winding data being also given for the respective solenoids.

TABLE 1.

Electrical Data of the Condenser Discharge Circuit for Special Experimental Solenoids A, B, and C respectively.

Solenoid	Resistance measured by direct current	Resistance at 500 cycles per second	Resistance of circuit leads	Total resistance of circuit (excluding mercury contacts)	Inductance at 500 cycles per sec.	Inductance of circuit leads	Total inductance of circuit, L	Condenser capacity in discharge circuit, C	Circuit constant, $\frac{1}{LC}$	Inductance of solenoid at radio frequencies	Calculated value of inductance of solenoid
	ohm	ohm	ohm	ohm	henry	henry	henry	μF		henry	henry
A	0·030	0·043	0·008	0·051	$\frac{27\cdot7}{10^6}$	$\frac{15\cdot7}{10^6}$	$\frac{43\cdot4}{10^6}$	339	68×10^6	$\frac{20\cdot3}{10^6}$ at $1\cdot1 \times 10^6$~ per sec.	—
B	0·083	0·090	0·008	0·098	$\frac{83\cdot6}{10^6}$	$\frac{16\cdot4}{10^6}$	$\frac{100}{10^6}$	1 366·6	$7\cdot32 \times 10^6$	$\frac{58\cdot5}{10^6}$ at $1\cdot25 \times 10^6$~ per sec.	$\frac{82\cdot8^*}{10^6}$
C	0·557	0·690	0·008	0·690	$\frac{377}{10^6}$	$\frac{16\cdot0}{10^6}$	$\frac{393}{10^6}$	339	$7\cdot48 \times 10^6$	$\frac{304}{10^6}$ at $0\cdot3 \times 10^6$~ per sec.	$\frac{384\dagger}{10^6}$

* Inductance of solenoid B calculated from Butterworth's formula (see "Dictionary of Applied Physics," vol. 2, p. 391; also see A. GRAY: "Absolute Measurements," 2nd edition, p. 520).
† Inductance of solenoid C calculated from Lyle's formula (see "Dictionary of Applied Physics," vol. 2, p. 389).

The electrical data for the condenser discharge circuit for each solenoid are given in Table 1.

It is to be noted that (as was pointed out in Section 1) the resistance of the mercury contact H (Fig. 1) introduced an increase in the calculated value of the effective resistance of the discharge circuit.

The actual effective resistance of the condenser discharge circuit was found from the logarithmic decrement of the current oscillograms, and the values so obtained for the three solenoids are given in Tables 2, 4 and 6 respectively.

As stated in Section 1, two sets of oscillograms were taken for each value of the potential to which the condensers were charged. One set of oscillograms gives the wave of P.D. which actually develops across the solenoid,* and the simultaneous wave of current in the solenoid. The second set gives the frequency of the

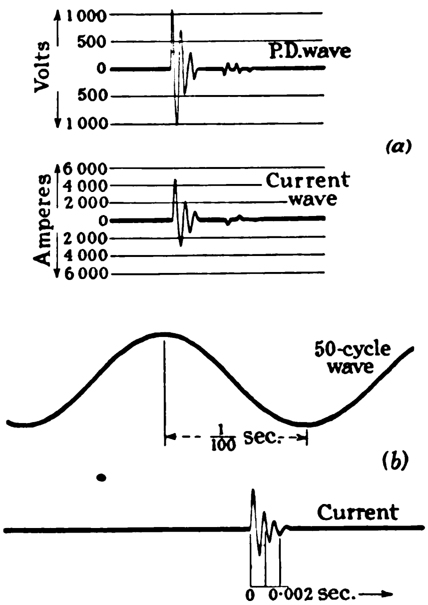

FIG. 4.

discharge current of the condensers. By means of these oscillograms it is possible to check the whole scheme of measurement of the current values by the oscillograph. For, knowing the value of the P.D. at the condenser terminals at the moment of discharge, the inductance of the discharge circuit including the solenoid and leads, the logarithmic decrement and also the frequency of the current wave, it is possible to calculate the effective resistance of the circuit. From a knowledge of the effective resistance, the magnitude of the first peak of the current wave can be calculated and then compared with the actual value as given by the oscillograms. Further, knowing the constants of the circuit, it becomes possible to calculate the frequency of the discharge current and to compare this calculated value with the frequency as actually measured from the oscillogram.

If any marked and consistent discrepancy occurs between the calculated and measured values of the current and frequency, and if this discrepancy cannot be explained in any other way, it is reasonable to suppose that some new phenomenon is having a marked effect on the result. As stated above, there is a marked discrepancy between the calculated and measured values for solenoid C but not for the other two solenoids. An attempt to find an adequate explanation for the discrepancy in the case of solenoid C is developed in Section 4.

Example.—In Fig. 4 the oscillograms refer to the case in which the condensers were charged to a P.D. of 2 126 volts and then discharged through the solenoid A. From both oscillograms the first peak of the current wave is found to be 4 520 amperes. The second peak of the current wave has a magnitude of 2 750 amperes.

The instantaneous value of the current at any time t subsequent to the commencement of the discharge is

$$i = \frac{V}{L\omega}e^{-\frac{1}{2}(R/L)t}\sin \omega t$$

where $$\omega = 2\pi f = \sqrt{\left[\frac{1}{LC} - \frac{R^2}{4L^2}\right]}$$

or $$f = \frac{1}{2\pi}\sqrt{\left[\frac{1}{LC} - \frac{R^2}{4L^2}\right]}$$

The magnitude I_1 of the first peak of the current wave is obtained by putting $t = 1/(4f)$, so that the magnitude of the first peak of the current wave is

$$I_1 = \frac{V}{L\omega}e^{-R/(8Lf)}$$

Similarly, the magnitude I_2 of the second peak is obtained by putting $t = 3/(4f)$, so that

$$I_2 = \frac{V}{L\omega}e^{-3R/(8Lf)}$$

and consequently $$\frac{I_2}{I_1} = e^{-R/(4Lf)}$$

Now it is found by measurement of the oscillogram (b) in Fig. 4 that the value of the frequency is

$$f = 1\,340 \text{ cycles per second,}$$

also, from the oscillograms in Fig. 4

$$\frac{I_2}{I_1} = 0\cdot 61,$$

from which it follows that

$$R = 0\cdot 114 \text{ ohm,}$$

since $$L = \frac{43\cdot 4}{10^6}\text{ henry}$$

Taking, then, the effective resistance of the discharge circuit to be $0\cdot 114$ ohm, the value of the first peak of the current wave and also the frequency may be calculated. Thus in this case,

$V = 2\,126$ volts; $L = 43\cdot 4 \times 10^{-6}$ henry; $C = 339\,\mu$F;

$$\left(\frac{1}{2}\frac{R}{L}\right)^2 = (1\,310)^2 = 1\cdot 73 \times 10^6$$

$$\omega = \sqrt{\left[\frac{1}{LC} - \left(\frac{1}{2}\frac{R}{L}\right)^2\right]} = 8\,150$$

that is, $f = 1\,300$ cycles per second.

* See also the discussion of the results obtained with solenoid A below, as to the effect of the connecting leads on the P.D. wave of the condenser discharge.

Substituting in the expression for the first current peak

$$I_1 = \frac{V}{L\omega} e^{-R/(8Lf)}$$

gives $\qquad I_1 = 4\,682$ amperes.

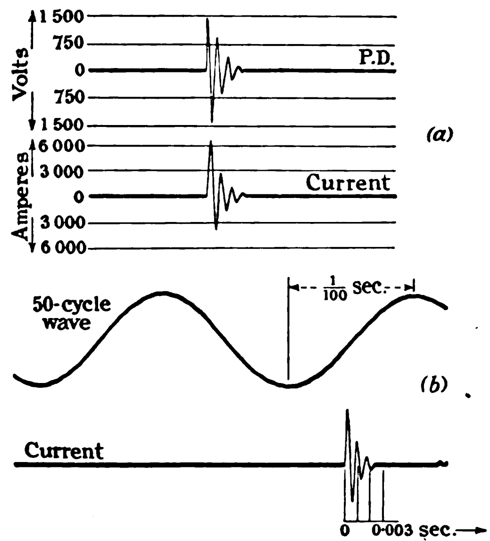

FIG. 5.

The calculated value of the first peak of the current wave is thus about 1·03 times the value measured from the oscillograms (*a*) and (*b*) in Fig. 4, whilst the calculated value of the frequency is about 0·97 of the value measured on the oscillogram (*b*), Fig. 4.

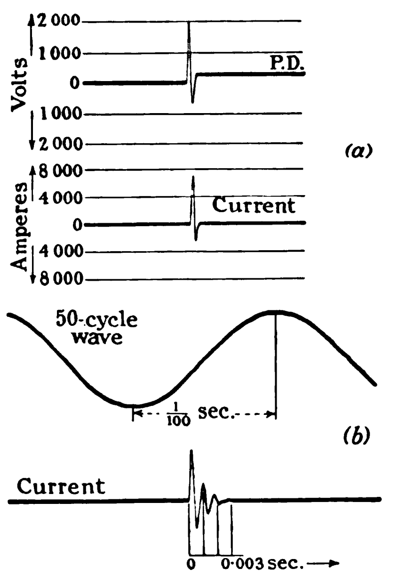

FIG. 6.

TESTS ON SOLENOID A.

For the tests on this solenoid the condensers were arranged in two equal sets. These two sets were connected in parallel for charging, and just before the discharge through the solenoid took place the two sets of charged condensers were connected in series (see Fig. 1).

The total capacity of the series arrangement of condensers was 339 μF.

Since each of the condenser units was capable of standing a P.D. of 2 000 volts, the terminal pressure of the series arrangement of the condensers could be taken as high as 4 000 volts.

A series of oscillograms were taken for this solenoid for a range of condenser discharge voltages from about 450 volts up to about 4 000 volts.

The series of oscillograms taken for this range of condenser discharge P.D.'s are reproduced in Figs. 4, 5 and 6.

In Table 2 are shown the data of the discharges as measured from the oscillograms, and several noteworthy facts are revealed by an examination of these data. These are :—

(i) The oscillograms giving the *pressure* wave of discharge show the curious result that the second peak of the wave is almost equal in magnitude to the first peak, the ratio of the magnitude of the second peak to that of the first peak being of the order of 0·90 throughout Table 2. This appears to be due to the fact that a relatively long length of cable is included between the tapping points for the P.D. strip of the oscillograph.

(ii) The magnitude of the resistance as deduced from the logarithmic decrement of the current wave is about 3 times the value of the resistance of the coil and leads. That is to say, the resistance of the mercury contact cup H (Fig. 1) appears to be much the larger portion of the total resistance of the circuit.

(iii) In the oscillogram, Fig. 4 (*a*), it is seen that the discharge of the condenser is interrupted and both the pressure across the solenoid and the current in the solenoid fall to zero for an appreciable time. The discharge is then continued for a short period and a second interruption then occurs after which the discharge becomes completed.

This effect appears to be due to the surging of the mercury in the large cup H (Fig. 1), whereby the contact with the switch becomes broken and then re-established. This same effect can be seen in the oscillograms of Fig. 5.

(iv) In the oscillogram (*a*) of Fig. 6 is seen the effect due to the bursting of the solenoid which occurred with the heavy current obtained from this discharge. It will be noted that the second current peak is relatively very small and falls rapidly to zero, after which the current ceases. The oscillogram of the P.D. wave, however, shows that after the solenoid has burst there is a pressure across the ends of the ruptured solenoid, i.e. the condensers have not become completely discharged.

It is of interest to note that only about 0·0005 sec. has elapsed between the closing of the discharge circuit and the rupturing of the solenoid. This gives an idea of the enormous mechanical forces developed by the discharge current which reached a peak value of about 7 000 amperes.

In order to measure the frequency for this condition of condenser discharge, a second solenoid was wound and another discharge obtained under the same conditions of condenser voltage. The oscillogram of this discharge is shown in (*b*), Fig. 6. This solenoid also burst when the discharge took place. It will be seen, however, in (*b*), Fig. 6 that the complete wave of current was obtained before the rupture occurred.

stants of the circuit and as measured from the oscillogram records. The agreement between the calculated and measured values is sufficiently close to make it impossible to detect any new phenomena due to the heavy values of the current discharge.

There is one other point worthy of notice in connection with the various P.D. oscillograms given in Figs. 4 (*a*) and 5 (*a*). Since the oscillograph P.D. strip was not connected directly across the solenoid terminals, there being a length of cable included in the circuit across which the P.D. strip was connected, the corresponding oscillograms consequently included the P.D. developed across this length of cable. Now for this solenoid the total length of wire in the winding was not very greatly in excess of the length of this included cable. The P.D. oscillograms do not therefore give an accurate measure of the P.D. across the solenoid terminals, the oscillogram being actually composed of the superposition of the current wave and a wave proportional to the P.D. wave.

TABLE 2.

Solenoid A. Values Measured from Oscillograms (Figs. 4–6).

Oscillogram Fig. No.	Condenser P.D. at commencement of discharge	Current wave			Pressure wave			Frequency	Resistance deduced from ratio $\frac{\text{2nd Current peak}}{\text{1st Current peak}}$	Maximum intensity of magnetic field generated at central part of solenoid core $H = k\frac{4\pi}{10} I \times 25\cdot3 = 22\cdot6 I$
		1st Peak	2nd Peak	Ratio $\frac{\text{2nd Peak}}{\text{1st Peak}}$	1st Peak	2nd Peak	Ratio $\frac{\text{2nd Peak}}{\text{1st Peak}}$			
	volts	amps.	amps.		volts	volts		~ per sec.	ohm	gauss
—	456	880	464	0·526	205	182	0·888	—	0·148	20 000
—	456	880	464	0·526	—	—	—	1 340		20 000
—	1 222	2 560	1 520	0·595	—	--	—	1 340	0·121	58 000
4 (*a*)	2 126	4 520	2 750	0·61	1 065	995	0·934	—	0·114	102 000
4 (*b*)	2 126	4 520	2 750	0·61	—	—	—	1 340		102 000
5 (*a*)	3 120	6 300	3 680	0·585	1 460	1 370	0·94	—	0·122	142 000
5 (*b*)	3 120	6 300	3 680	0·585	—	—	—	1 310		142 000
6 (*a*)	3 944	6 930	—	—	1 880	—	—	—	0·118	156 000*
6 (*b*)	3 944	7 240	4 040	0·558	—	—	—	1 160		163 000†

* Coil burst. † Coil burst (i.e. L increased, and hence f and also I decreased).

TABLE 3.

Solenoid A.

Oscillogram, Fig. No.	Condenser P.D. at commencement of discharge	1st Peak of current wave		Frequency	
		Calculated	Measured (see Table 2)	Calculated	Measured (see Table 2)
	volts	amps.	amps.	~ per sec.	~ per sec.
—	456	930	880	1 285	1 340
—	1 222	2 650	2 560	1 292	1 340
4 (*b*)	2 126	4 680	4 520	1 296	1 340
5 (*b*)	3 120	6 780	6 300	1 285	1 310
6 (*b*)	3 944	8 360	7 240	1 270	1 160*

* Coil burst.

NOTE.—Calculated values of current and frequency given in this table are deduced from the circuit constants $C = 339\ \mu F$; $L = 43\cdot4 \times 10^{-6}$ henry; $1/(LC) = 68\cdot0 \times 10^{6}$. R taken from Table 2.

In Table 3 is given a comparison of the values of the current and frequency as calculated from the con-

TESTS ON SOLENOID B.

The measurements made with this solenoid were carried out with the condensers all connected in parallel at discharge, the total condenser capacity being $1366\cdot6\ \mu F$.

Oscillograms were taken for the discharge through the solenoid for a range of condenser discharge voltages from about 250 volts to 1 800 volts.

In Table 4 the measurements of the condenser discharge are shown as obtained from the respective oscillograms. In these discharges the peculiarity in the P.D. wave noticed in the case of solenoid A, viz. the closeness of the magnitudes of the first and second peak values, has become much less marked (see Table 4). This fact gives further support to the view that in the case of solenoid A the effect is due to a superposition of current and P.D. waves in the relatively long cable included between the tapping points of the oscillograph P.D. strip.

In Table 5 a comparison is shown of the values of the current and frequency as calculated from the constants of the circuit and as measured from the oscillograms. Here, again, the agreement between the calculated values and those measured from the oscillograms is sufficiently close to make any incipient new phenomena due to the heavy value of current discharges not pronounced enough to be decisively recognizable.

Table 4.

Solenoid B. Values Measured from Oscillograms.

Condenser P.D. at commencement of discharge	Current wave			Pressure wave			Frequency	Resistance deduced from ratio $\frac{\text{2nd Current peak}}{\text{1st Current peak}}$	Maximum intensity of magnetic field generated at central part of solenoid core $H = k\frac{4\pi}{10}I \times 26 \cdot 4 = 30 \cdot 7\,I$
	Magnitude of		Ratio $\frac{\text{2nd Peak}}{\text{1st Peak}}$	Magnitude of		Ratio $\frac{\text{2nd Peak}}{\text{1st peak}}$			
	1st Peak	2nd Peak		1st Peak	2nd Peak				
volts	amps.	amps.		volts	volts		~ per sec.	ohm	gauss
250	640	—	—	—	—	—	—	0·119	19 700
	640	240	0·375	—	—	—	435	0·119	19 700
404	1 130	465	0·43	295	178	0·60	—	—	34 700
880	2 340	1 230	0·525	690	—	—	—	0·112	72 000
	2 340	1 230	0·525	—	—	—	440	0·112	72 000
1 063	3 000	1 515	0·505	830	560	0·67	—	0·124	92 000
	3 000	1 515	0·505	—	—	—	454	0·124	92 000
1 260	3 540	1 800	0·51	—	625	—	—	0·119	109 000
	3 540	1 800	0·51	—	—	—	444	0·119	109 000
1 430	3 750	1 875	0·50	995	650	0·66	—	0·122	115 000
	3 750	1 875	0·50	—	—	—	440	0·122	115 000
1 630	4 560	2 150	0·47	1 220	775	0·635	—	0·133	140 000
1 800	4 910	2 500	0·51	1 360	880	0·650	—	0·114	151 000
	4 910	2 500	0·51	—	—	—	410	0·114	151 000

Table 5.

Solenoid B.

Condenser P.D. at commencement of discharge	First peak of current wave		Frequency	
	Calculated	Measured (see Table 4)	Calculated	Measured (see Table 4)
volts	amps.	amps.	~ per sec.	~ per sec.
250	580	640	408	435
880	2340	2410	420	440
1063	3000	2790	420	454
1260	3540	3360	420	444
1430	3750	3830	420	440
1800	4910	4870	420	410

Note.—Calculated values of current and frequency given in this table are deduced from the circuit constants $C = 1\,366 \cdot 6\mu\text{F}$; $L = 100 \times 10^{-6}$ henry; $1/(LC) = 7 \cdot 32 \times 10^{6}$. R taken from Table 4.

Tests on Solenoid C.

This solenoid was wound to give much greater intensities of magnetic fields than either of the other two solenoids. The core of the bobbin was of much smaller diameter and the number of turns per cm length of winding was about 8 times greater than the value for either of the other solenoids. It was thus possible to obtain a given intensity of magnetic field without the necessity for such large values of the discharge currents as were obtained in the previous cases. An advantageous feature of this is that the mercury in the large contact cup was subject to much less disturbance at the moment of making contact; this is shown in the oscillograms by the fact that no marked interruptions of the current due to the condenser discharges are apparent.

For this solenoid the condensers were all charged in parallel and arranged in two equal sets in series for the discharge, the total capacity of the series connection being 339 μF. Discharges were obtained for a range of condenser voltages from 259 volts to 4 220 volts.

In Table 6 the data of these discharges are shown as deduced from the respective oscillograms. It will be noticed that an intensity of magnetic field of nearly $0 \cdot 5 \times 10^{6}$ gauss was obtained at the highest voltage of condenser discharge. At this discharge the solenoid burst.

Table 7 shows a comparison of the values of the current and frequency as deduced from the constants of the discharge circuit, and the actually measured values as given in Table 6.

The noteworthy feature about the data in Table 7 is the large discrepancy between the calculated values and the observed values. In view of the relatively good agreement of the calculated and measured values in the cases of solenoids A and B respectively, it appears that some new effect is manifesting itself in the performance of this solenoid. This new effect seems to be

equivalent to a reduction in the effective inductance of the solenoid.

In attempting to locate the cause of this it should be borne in mind that the conditions for this solenoid are different from those for solenoids A and B respectively, in that the magnetic fields generated in the core of solenoid C attain a much greater intensity than those generated in either solenoid A or B. The effect of this is that the mechanical pressure developed between neighbouring turns of the solenoid winding is very much greater. Further, the total length of wire in the winding of solenoid C is much greater than in either of the other two solenoids.

The conditions therefore may be summarized as follows: In solenoid C there are a large number of turns of wire insulated with cotton and soaked in oil. These turns all become pressed together with a very great mechanical force when the condenser discharge currents pass through the winding, and moreover, since the discharge currents are oscillatory, the mechanical force which presses the oil-soaked cotton against the wire will also be a periodic force.

TABLE 6.

Solenoid C. Values Measured from Oscillograms.

Condenser P.D. at commencement of discharge	Current wave			Pressure wave			Frequency	Resistance deduced from ratio 2nd Current peak / 1st Current peak	Maximum intensity of magnetic field generated at centre part of solenoid core $H = k\frac{4\pi}{10}wI = 106I$
	1st Peak	2nd Peak	Ratio 2nd Peak / 1st Peak	1st Peak	2nd Peak	Ratio 2nd Peak / 1st Peak			
volts	amps.	amps.		volts	volts		~ per sec.	ohms	gauss
259	146	43	0·291	190	77	0·405	—	—	15 500
	168	38	0·226	—	—	—	418	0·985	17 800
454	280	57	0·204	365	146	0·400	—	—	29 700
	280	84	0·300	—	—	—	456	0·865	29 700
1 042	740	261	0·355	—	426	—	—	—	78 500
	740	222	0·300	930	383	0·413	—	—	78 500
	740	182	0·246	—	—	—	446	0·980	78 500
2 138	1 320	382	0·278	1 850	805	0·435	—	—	140 000
	1 320	385	0·292	—	—	—	445	0·865	140 000
3 104	1 760	365	0·208	2 530	875	0·346	—	—	187 000
	1 760	336	0·191	—	—	—	425	1·11	187 000
4 220	2 150	—	—	3 430	—	—	—	—	228 000*

* Coil burst.

TABLE 7.

Solenoid C.

Condenser P.D. at commencement of discharge	First peak of current wave		Frequency	
	Calculated	Measured (see Table 6)	Calculated	Measured (see Table 6)
volts	amps.	amps.	~ per sec.	~ per sec.
259	120	168	387	418
454	231	280	400	456
1 042	606	740	413*	—
1 042	495	740	398	446
2 138	1 090	1 320	400	445
3 104	1 320	1 760	373	425

* Resistance $R = 0{\cdot}69$ ohm, deduced from ratio $I_2/I_1 = 0{\cdot}355$ (see Table 6).

NOTE.—Calculated values of current and frequency given in this table are deduced from the circuit constants $C = 340\ \mu F$; $L = 393 \times 10^{-6}$ henry; $1/(LC) = 7{\cdot}48 \times 10^6$. R taken from Table 6.

In Section 4 an attempt is made to outline an explanation of the apparent effective reduction of the inductance of this solenoid on the basis of the contact E.M.F. developed between the wire and the oil-soaked cotton insulation which is pressed into intimate contact with the wire.

Section 3. THE INFLUENCE OF A CHANGE IN THE DIMENSIONS OF THE SOLENOID WINDING ON THE INTENSITY OF THE MAGNETIC FIELD GENERATED WITHIN THE CORE OF THE SOLENOID.

It is of interest to inquire what effect any variation in the design of the solenoid may be expected to have on the maximum intensity of magnetic field which may be obtained.

In this connection it is to be observed that, as the leads to the coil from the condensers must have a certain inductance and resistance and, in particular, since the mercury contact resistance is relatively considerable, it is not at first sight obvious what are the best proportions to give the solenoid.

For the particular purpose in view, for which the present investigation has been undertaken, it is to be remembered that the size of the magnetic sample which is to be submitted to the intense field must not be too small, otherwise it becomes very difficult to test its

magnetic properties with sufficient accuracy. This consideration places a limit on the internal diameter of the solenoid tubular core within which the test sample is placed. Further, in order that the field shall be reasonably uniform in the space within the core which is occupied by the sample, the length of the solenoid must not be too small.

The solenoid winding cannot therefore be expected to have a smaller internal diameter or a shorter length than the values given in Fig. 3 for solenoid C. That is to say, the winding will be not less than 1 cm long and not less than $\frac{3}{16}$ in. internal diameter. These values have consequently been taken as fixed, and the inductance of the leads is assumed to be fixed at 15×10^{-6} henry.

The mercury cup contact resistance is assumed to be negligibly small.

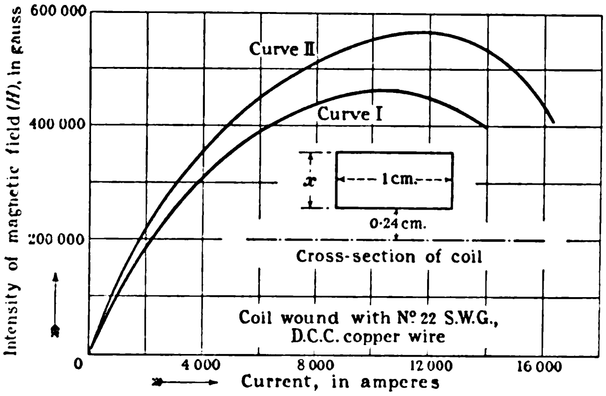

FIG. 7.

Curve I.—Condenser capacity = 1 360 μF; condensers charged to 2 000 volts.
Curve II.—Condenser capacity = 340 μF; condensers charged to 4 000 volts.

From calculations of the inductance and resistance of the solenoid for a series of values of x, the radial depth of the winding, the author has worked out the relationship between the first peak of the discharge current in the solenoid and the corresponding values of the magnetic intensity at the central part within the core of the solenoid. The solenoid is wound with No. 22 S.W.G. d.c.c. copper wire.

The results are plotted in Fig. 7 as curves I and II. Two cases have been considered, viz.

(1) Curve I refers to the case in which the condenser capacity is 1 360 μF, the condensers being charged to 2 000 volts.

(2) Curve II refers to the case in which the condenser capacity is 340 μF, the condensers being charged to 4 000 volts. This corresponds to charging the whole bank of 1 360 μF in parallel at 2 000 volts and discharging them as two equal banks in series.

As an example of the significance of these results, the data given in Table 8 will serve.

Reference to Fig. 7 shows some interesting facts. First of all, other things remaining the same, there is a value for the winding depth x which gives the maximum value for the intensity of the magnetic field within the solenoid core. Next, it is seen that the device of

TABLE 8.

Solenoid Wound with No. 22 S.W.G. Copper Wire [*see Curve II* (*Fig.* 7)].

Radial winding depth	Number of turns per cm length, w	Magnitude of first peak of condenser discharge current wave, I_1	Magnetic intensity corresponding to first peak of current wave $H = k\frac{4\pi}{10}I_1w$
cm		amps.	gauss
0·25	25	16 240	413 000
1·0	100	6 000	446 000
3·0	300	1 080	130 000

charging the condensers in parallel and connecting them in two groups in series for discharging gives a distinctly larger value for the maximum value of the magnetic field within the core. By carrying this procedure still farther and, for example, by charging the condensers all in parallel and then dividing them into 4 groups in series before discharging, still higher values for the maximum intensity of the magnetic field generated within the solenoid core may be expected.

Section 4. AN ATTEMPT TO EXPLAIN THE DISCREPANCY BETWEEN THE CALCULATED AND MEASURED VALUES OF THE CONDENSER DISCHARGE CURRENTS IN SOLENOID C, ON THE BASIS OF THE CONTACT E.M.F. DEVELOPED BETWEEN THE WIRE AND THE OIL-SOAKED COTTON INSULATION.

The author advances the theory that the so-called "frictional" electricity or "contact E.M.F." which is developed when any two unlike substances are brought into intimate contact * is sufficient to account for the apparent decrease of the inductance of solenoid C, as shown by the discrepancy between the measured values of current and frequency given in Table 7 and the calculated values of the same quantities also given in Table 7. A reduction in the effective inductance would, in fact, mean an increase in the frequency and (within limits) an increase in the current also.

Referring to Fig. 8, suppose that a strip of metal AB is pressed into intimate contact with a layer of oil-soaked cotton wool, and also suppose that, by virtue of the contact E.M.F., the metal becomes thereby negatively electrified and the cotton positively electrified.

In Fig. 9 this is illustrated by showing the potential of the cotton by a horizontal straight line below the datum line, this datum line being intended to represent the potential of the centre of the metal strip.

Now suppose that a potential difference is established between the two ends of the metal strip, e.g. by connecting them to a source of direct-current supply. Since the oil-soaked cotton is an insulator, it cannot, of course, allow a conduction current to pass. The contact E.M.F., however, between the metal and the cotton will tend to remain constant and it follows,

* See ELIHU THOMSON: *General Electric Review*, 1922, vol. 25, p. 418; also *Elektrotechnische Zeitschrift*, 1924, vol. 45, p. 878.

therefore, that a current will flow across the contact surface of metal and oil-soaked cotton.

This current will be so directed as to maintain a uniform value of the contact E.M.F. between the metal and the oil-soaked cotton at every point of the surface of contact. Thus, if the end A of the metal is raised to a positive potential and the end B lowered to a

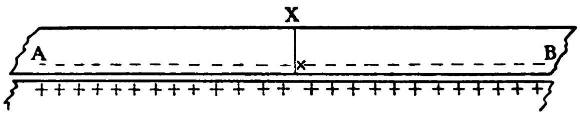

FIG. 8.

negative potential with respect to the datum XX, there will be a flow of electricity *from the metal into the cotton* at points along the contact surface between the end A and the centre X, and there will be a flow of electricity *from the cotton into the metal* at points along the contact surface between the end B and the centre X.

If now the source of d.c. potential is removed from

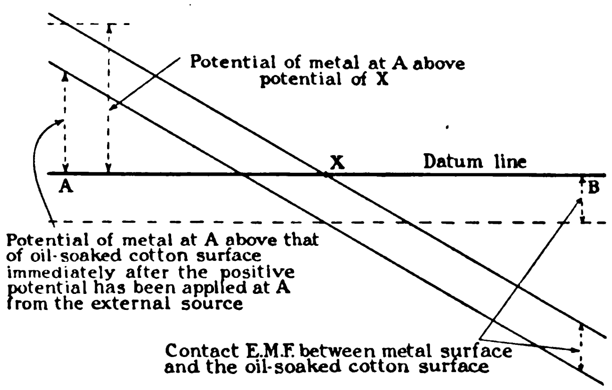

FIG. 9.

the ends A, B, the metal will immediately become an equipotential surface and, in order that the characteristic contact E.M.F. between the cotton and metal surfaces shall be maintained, there will be a flow of electricity *from the cotton into the metal* at points along the surface between the end A and the centre X, and a flow of electricity *from the metal into the cotton* at points along the surface between the end B and the centre X. It thus appears that the cotton insulation stores up energy and releases it in a precisely similar way to that in which a condenser stores and releases electrical energy.

This condenser effect due to the contact E.M.F. must not, however, be confused with the ordinary self-capacity of a coil. In the case of ordinary self-capacity effects the condenser is a normal one comprising two conductors separated by a non-conductor. In the case of the contact E.M.F. condenser effects, however, the condenser has only one metal plate, and the cotton surface itself forms the other plate. The distance between the plates thus becomes one of atomic dimensions.*

Since the contact E.M.F. is relatively high, viz. of the order of 1 volt, and since the distance between the equivalent plates of this contact E.M.F. condenser is of atomic dimensions, it follows that the capacity may become relatively enormous.

The total value for any given solenoid, of this capacity due to the contact E.M.F. effect, will depend upon the total surface of the side of the coil and the mechanical pressure with which the wire surface is forced on to the oil-soaked cotton. Since, in the case of solenoid C, both the surface contact area and the mechanical pressure of contact are very much greater than in either of the solenoids B and A, this contact E.M.F. condenser effect will be correspondingly greater for solenoid C than for either of the other two solenoids.

Preliminary attempts have been made to check this theory of a contact E.M.F. condenser, the method adopted being to build up a special solenoid and make one end flange adjustable so that very large mechanical pressures can be exerted to press the windings into close contact. By supplying alternating current at 50 frequency, endeavours were made to produce a leading current when great mechanical pressure was applied to the end flange of the coil. Up to the present this experiment has not been successfully accomplished, but it is hoped that it may be possible to renew the attempt at an early date.

Section 5. SOLENOID WOUND ON A STEEL BOBBIN.

An interesting oscillogram is shown in Fig. 10, which refers to a solenoid wound on a steel bobbin. The condensers were connected all in parallel, charged up to 2 126 volts and then connected in two sets in series for discharging. The coil burst when the discharge took place and the oscillogram of Fig. 10 shows the sequence of events after the discharge circuit was closed.

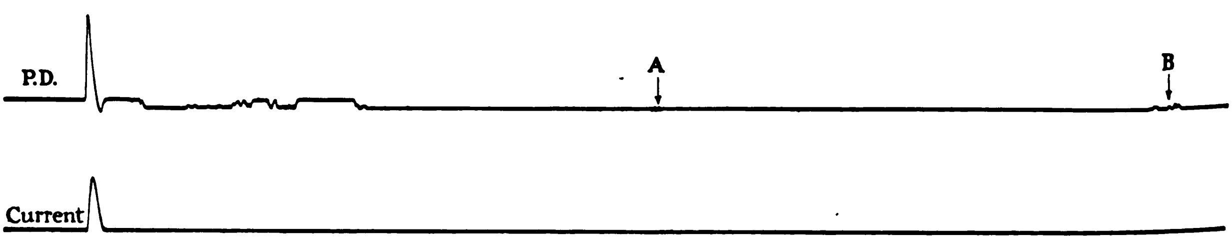

FIG. 10.

The current wave comprises a single peak and then falls to zero. The peak value of the current wave as measured from the oscillogram is found to be 2 230 amperes.

* See ELIHU THOMSON, *loc. cit.*

The P.D. wave shown in the oscillogram exhibits some remarkable features. For example, the P.D. becomes zero at the same time that the current falls to zero, and the P.D. remains zero for about 0·002 sec. The P.D. oscillogram then shows high-frequency ripples of small amplitude, afterwards becoming definitely negative and remaining negative for about 0·005 sec. The P.D. then becomes oscillatory and reaches the zero value, remaining zero for about 0·001 sec. After further fluctuations the P.D. again becomes definitely negative and remains negative but develops occasional ripples of high frequency and small amplitude (see A, B, Fig. 10).

The curious activity of the P.D. after the current has ceased to flow appears to be definitely due to the iron of the bobbin. This is evident from the fact that when a solenoid of similar winding data but wound on an ebonite bobbin burst [see Fig. 6 (*a*), solenoid B], no such high-frequency ripples were developed in the P.D.

It would further appear that the atomic disturbance of the material of the bobbin took some considerable time to settle down to a state of quiescence, that is, in so far as its external effects are concerned.

It is hoped to obtain, at a later date, further experimental data relative to these curious phenomena in the P.D. wave.

Concluding Remarks.

As previously stated, the prime purpose for which this method of generating very intense magnetic fields was devised was to ascertain the effect of repeated application of such fields on a magnetic substance. For this purpose, the magnetic specimen is prepared in the form of a short tube of approximately the following dimensions: Length $\frac{3}{16}$ in., internal diameter $\frac{1}{8}$ in., external diameter $\frac{3}{16}$ in.

The specimen is inserted in the hollow core of a solenoid which is wound on a steel bobbin. The bobbin has a longitudinal slit to minimize the generation of eddy currents in the metal of the bobbin.

Before subjecting the specimen to the intense magnetic fields the magnetization (i.e. the *B-H*) curve is determined. The specimen is then inserted in the tubular core of the solenoid and the oscillating switch E, Fig. 1, is set in operation so that a condenser discharge passes through the solenoid about once every 5 minutes. After a few hundred discharges have in this way taken place, the specimen is removed and its magnetization curve is again determined.

It has been found that the magnetization curve for a specimen of stalloy is distinctly improved after having been subjected to the intense magnetic fields in this way.

This process is being carried out for a long period of time to ascertain what limit, if any, there is to the observed change in the magnetization curve due to the repeated application of the very intense magnetic fields.

Tests will also be made on specimens of bismuth and other representative materials.

RECURRENT CIRCUITS; A METHOD OF SOLUTION.*

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(*Paper first received 26th November, 1925, and in final form 23rd February, 1926.*)

SUMMARY.

The paper consists of the statement and illustration of a method of solving recurrent circuits (of which the filter is the simplest example) when operating in the "steady-state" condition, by reducing each element to a "rejector" resonant at the operating frequency.

The method is stated and is illustrated by the "low-pass" and "high-pass" filters. The general case of a filter is solved. Characteristics of the simpler types of filters are stated briefly.

The initial sending-end impedance of the line and the condition for non-reflection are written down from inspection. It is shown that, for one-way working, it is not necessary, or desirable (as is often stated), that the transmitter, receiver, and initial sending-end impedances should all be equal.

Line distortion due to reflection is considered briefly.

A worked example is given in the Appendix.

Although the method is applied here to filters only, it is readily extended to both continuous and loaded lines.

In the following method of treatment of lines consisting of recurrent circuits, no results are obtained which are not already well known, but it is believed that the method of obtaining them is novel and capable of more extended application. It would appear, too, that the method is more direct than that usually employed, and the physical properties of the circuits are kept clearly in view.

The following simple principles are used :—

(1) Any impedance may be replaced by two parallel impedances connected between the same points, the two together taking the same current in the same phase as the original impedance. There is no objection, from an analytical point of view, to one of these impedances including a negative resistance (there is now, in fact, little objection from a practical point of view).

Utilizing this principle it is possible to render every recurrent unit of a circuit of zero circuital impedance.

(2) A circuit which has a zero circuital impedance is of infinite impedance between any two points which are separated by paths neither of whose impedances is zero. (This principle is self-evident when the circuit is isolated and not coupled to any other. For the present it is sufficient to consider that case. It will, however, be shown later that, under the conditions obtaining in recurrent circuits, an equivalent self-inductance can be imagined included in each unit of the circuit to replace the mutual inductance. In this sense the term "effective impedance" is used.)

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(3) An infinite impedance may be connected between any two points in a circuit without producing any change in the circuit.

The application of these principles is, briefly, as follows. Fig. 1 represents any recurrent circuit, where Z_1 and Z_2 are impedances of the most general type; they may include the effective impedance introduced by any magnetic or capacity coupling between successive sections.

Let us imagine Z_2 to be replaced by two parallel

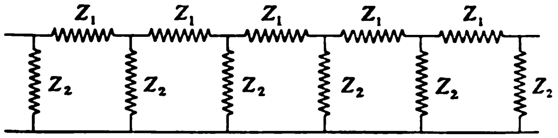

FIG. 1.

impedances, Z_2' and Z_2'', which must necessarily conform to the relation

$$\frac{1}{Z_2'} + \frac{1}{Z_2''} = \frac{1}{Z_2} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If, to define Z_2' and Z_2'' completely, it be stipulated that

$$Z_2' + Z_2'' + Z_1 = 0 \quad . \quad . \quad . \quad . \quad (2)$$

then the network has been resolved into a number of similar units, each resonant to the particular operating frequency considered (Fig. 2).

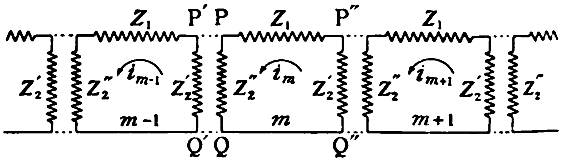

FIG. 2.

Considering the unit m, its circuital impedance is zero, and its impedance between the points P and Q (or P″ and Q″) infinite. Its connection to the unit $m-1$ at the points PP′, QQ′ in no way changes the impedance of either unit, but a further necessary condition follows, since the potentials across PQ and P′Q′ are equal, viz.

$$i_m Z_2'' = -i_{m-1} Z_2' \quad . \quad . \quad . \quad . \quad (3)$$

It therefore follows that the currents in successive units bear to one another the constant ratio

$$e^k \equiv -\frac{Z_2'}{Z_2''} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

whence it follows that one solution of the circuit is afforded by the equation

$$i_n = Ae^{nk} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Noting that equations (1) and (2) constitute a quadratic relation symmetrical in Z_2' and Z_2'', it follows that

$$i_n = Be^{-nk} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

is also a solution and that, in general, the current i_n will be made up of two components and may be expressed as

$$i_n = Ae^{nk} + Be^{-nk} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The current consists of two trains, one travelling from the source, the other towards it, each equally and uniformly decrescent in its direction of travel. The constants A and B are fixed by the terminal conditions.

Very long line.—In the case of an infinite line supplied from one end

$$i_\infty = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

whence either A or B must be zero. In a long line i_n approaches zero at distances remote from the ends,

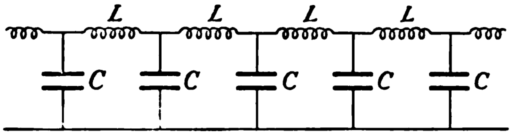

FIG. 3.

whether the line is supplied from one end only, or from both. A doubly-fed long line may be considered practically to be two infinite lines joined at their far ends.

The index k, determined by equations (1), (2) and (3), may be real, imaginary or complex, according to the natures of Z_2' and Z_2''. The equations are equally satisfied by the value $-k$. We may, therefore, define which solution we shall call k, and which $-k$. If we stipulate that the real part of k shall be negative, then it is clear that, for an infinite line, B in equation (7) must be zero and equation (5) is the one applicable.

Before proceeding to the general case the method may be illustrated conveniently by two comparatively simple cases.

Infinitely long " low-pass " filter.

Case 1. *Resistance zero.*—This circuit is represented by Fig. 3. For it equations (1) and (2) become

$$C' + C'' = C \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and

$$\frac{1}{\omega C'} + \frac{1}{\omega C''} - \omega L = 0 \quad . \quad . \quad . \quad (10)$$

whence

$$\omega = 1\Big/\sqrt{\left(L\frac{C'C''}{C'+C''}\right)} \quad . \quad . \quad . \quad (11)$$

Since $C'C''/(C'+C'')$ cannot exceed $\frac{1}{4}C$ if C' and C'' are *real* fractions of C, we see that, if we define

$$\Omega \equiv 1/\sqrt{(LC)} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

real values of C' and C'' can be determined so long as $\omega > 2\Omega$, but if $\omega < 2\Omega$ the values of C' and C'' must be imaginary or complex.

From equations (9), (10) and (12) we obtain

$$\left.\begin{aligned} C' &= \frac{C}{2}\left[1 + \sqrt{\left\{1 - \frac{4\Omega^2}{\omega^2}\right\}}\right] \\ C'' &= \frac{C}{2}\left[1 - \sqrt{\left\{1 - \frac{4\Omega^2}{\omega^2}\right\}}\right] \end{aligned}\right\} \quad . \quad . \quad (13)$$

If $\omega > 2\Omega$ both these values are real and positive and we have

$$e^k = -\frac{1 - \sqrt{\left\{1 - \frac{4\Omega^2}{\omega^2}\right\}}}{1 + \sqrt{\left\{1 - \frac{4\Omega^2}{\omega^2}\right\}}} \quad . \quad . \quad (14)$$

Since this expression must be negative there is a change to antiphase between sections. The numerical value of the attenuation is usually expressed

$$k = \text{arc cosh}\left(\frac{\omega^2}{2\Omega^2} - 1\right) \quad . \quad . \quad . \quad (15)$$

which follows from equation (14).

If $\omega < 2\Omega$ the determined values C' and C'' of equation (13) are complex and may be expressed as

$$\left.\begin{aligned} C' &= \frac{C}{2}\left[1 + j\sqrt{\left\{\frac{4\Omega^2}{\omega^2} - 1\right\}}\right] \\ C'' &= \frac{C}{2}\left[1 - j\sqrt{\left\{\frac{4\Omega^2}{\omega^2} - 1\right\}}\right] \end{aligned}\right\} \quad . \quad . \quad (16)$$

The physical meaning of these is clear. The condenser C is divided into two equal parts, one of which is shunted by a positive resistance, the other by an equal negative resistance.

$$e^k = -\frac{1 - j\sqrt{\left\{\frac{4\Omega^2}{\omega^2} - 1\right\}}}{1 + j\sqrt{\left\{\frac{4\Omega^2}{\omega^2} - 1\right\}}} \quad . \quad . \quad (17)$$

The numerical value of this is unity so that there is no attenuation. But there is a phase change.

Writing

$$e^k \equiv e^{\gamma + j\delta} \equiv \frac{ja - 1}{ja + 1} \equiv \frac{a^2 - 1 - 2ja}{a^2 + 1} \quad . \quad (18)$$

where $a^2 = (4\Omega^2/\omega^2) - 1$ [from (17)] we have

$$\cos\delta = \frac{a^2 - 1}{a^2 + 1} = 1 - \frac{\omega^2}{2\Omega^2} \quad . \quad . \quad . \quad (19)$$

where δ is the phase change.

The numerical values of the attenuation for various frequencies are shown in Fig. 4.

Case 2. *Inductances having resistance.*—For this case equations (1) and (2) become $C' + C'' = C$ (9)

$$-\frac{j}{\omega C'} - \frac{j}{\omega C''} + j\omega L + R = 0 \quad . \quad . \quad (20)$$

whence

$$\left.\begin{aligned} C' &= \frac{C}{2}\left[1+\sqrt{1-\frac{4\Omega^2}{\omega^2}\left\{\left(1+\frac{jR}{\omega L}\right)\Big/\left(1+\frac{R^2}{\omega^2L^2}\right)\right\}}\right] \\ C'' &= \frac{C}{2}\left[1-\sqrt{1-\frac{4\Omega^2}{\omega^2}\left\{\left(1+\frac{jR}{\omega L}\right)\Big/\left(1+\frac{R^2}{\omega^2L^2}\right)\right\}}\right] \end{aligned}\right\} \quad (21)$$

Writing

$$\sqrt{\left[1-\frac{4\Omega^2}{\omega^2}\left\{\left(1+\frac{jR}{\omega L}\right)\Big/\left(1+\frac{R^2}{\omega^2L^2}\right)\right\}\right]} \equiv \sqrt{(A+jB)} \equiv P+jQ \quad . \quad (22)$$

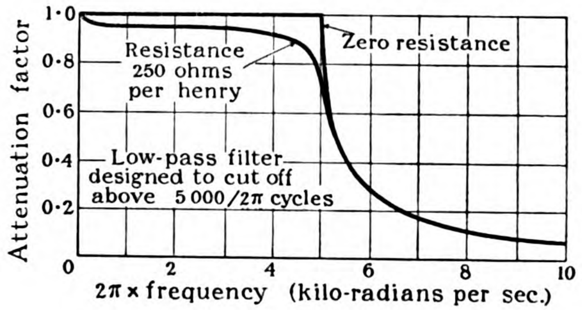

FIG. 4.

we have

$$\left.\begin{aligned} P^2 &= \frac{+\sqrt{(A^2+B^2)}+A}{2} \\ Q^2 &= \frac{+\sqrt{(A^2+B^2)}-A}{2} \end{aligned}\right\} \quad . \quad . \quad (23)$$

and

$$e^k = -\frac{1-(P+jQ)}{1+(P+jQ)} \quad . \quad . \quad . \quad (24)$$

and

$$[e^k]_{num.} = \frac{\sqrt{\{(1-P)^2+Q^2\}}}{\sqrt{\{(1+P)^2+Q^2\}}} \quad . \quad . \quad (25)$$

An examination of these expressions shows that P cannot be zero unless R is zero, and there is always attenuation. The value of that attenuation is plotted

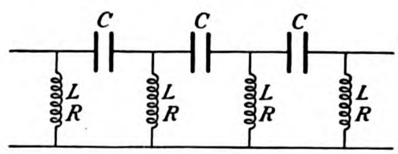

FIG. 5.

in Fig. 4 for the case in which the resistance is 250 ohms per henry, the cut-off frequency being designed to be 5 000/(2π).

Infinitely long "high-pass" filter.—For this case (shown in Fig. 5) equations (1) and (2) become

$$\frac{1}{Z_2'}+\frac{1}{Z_2''}=\frac{1}{j\omega L+R} \quad . \quad . \quad . \quad . \quad (26)$$

$$Z_2'+Z_2''-\frac{j}{\omega C}=0 \quad . \quad . \quad . \quad . \quad (27)$$

whence

$$\left.\begin{aligned} Z_2' &= \frac{j}{\omega C}\left[1-\sqrt{\left\{1-\frac{4\omega^2}{\Omega^2}\left(1-\frac{jR}{\omega L}\right)\right\}}\right] \\ Z_2'' &= \frac{j}{\omega C}\left[1+\sqrt{\left\{1-\frac{4\omega^2}{\Omega^2}\left(1-\frac{jR}{\omega L}\right)\right\}}\right] \end{aligned}\right\} \quad (28)$$

If the inductances have no resistance it is clear that for frequencies greater than ½Ω there is no attenuation, but for frequencies below ½Ω

$$e^k = -\frac{1-\sqrt{\left\{1-\frac{4\omega^2}{\Omega^2}\right\}}}{1+\sqrt{\left\{1-\frac{4\omega^2}{\Omega^2}\right\}}} \quad . \quad . \quad . \quad (29)$$

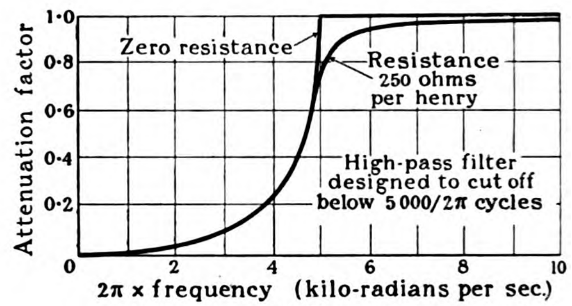

FIG. 6.

When the inductances have resistance we may write

$$\sqrt{\left[1-\frac{4\omega^2}{\Omega^2}\left(1-\frac{jR}{\omega L}\right)\right]} \equiv (A+jB) \equiv P+jQ \quad (30)$$

Equations (23), (24) and (25) then afford the solution. Values are plotted in Fig. 6.

General case.—The most commonly occurring general case is that of the T section line with a finite number of sections in which each unit may be supposed to possess a mutual inductance to immediately adjacent units (Fig. 7).

For this circuit we have

$$\frac{1}{Z_2'}+\frac{1}{Z_2''}=\frac{1}{Z_2} \quad (1)$$

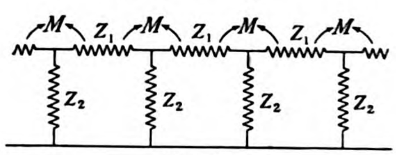

FIG. 7.

Corresponding to equation (2) we have

$$i_m(Z_1+Z_2'+Z_2'')+j\omega M i_{m-1}+j\omega M i_{m+1}=0 \quad (31)$$

We have also

$$\left.\begin{aligned} Z_2'' i_m &= -Z_2' i_{m-1} \\ Z_2' i_m &= -Z_2'' i_{m+1} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (32)$$

Substituting (32) in (31) we obtain

$$Z_1+Z_2'+Z_2''-j\omega M\left(\frac{Z_2'}{Z_2''}+\frac{Z_2''}{Z_2'}\right)=0 \quad . \quad (33)$$

The effective impedance introduced by magnetic coupling is shown by equations (32) and (33). We may imagine, as is indicated in Fig. 8, that the impedance of each section is increased by amounts $j\omega Me^k$ and $j\omega Me^{-k}$.

Equations (1) and (33) are sufficient to determine the solution in the form of equation (7), the constants being fixed by the terminal conditions.

It may, however, be worth while to indicate the method of determining the general attenuation per section. For convenience let us write

$$\left.\begin{aligned} Z_1 &\equiv b \\ Z_2 &\equiv a \\ j\omega M &= c \\ Z_2' &\equiv x \\ Z_2'' &\equiv y \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (34)$$

The general attenuation is then $-x/y$.

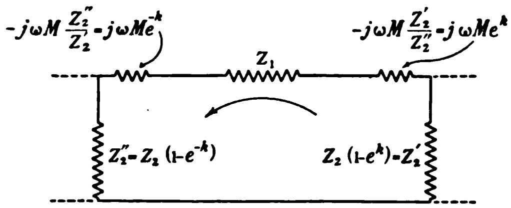

FIG. 8.

On substitution, equations (1) and (33) become

$$\left.\begin{aligned} \frac{1}{x} + \frac{1}{y} &= \frac{1}{a} \\ b + x + y - c\left(\frac{x}{y} + \frac{y}{x}\right) &= 0 \end{aligned}\right\} \quad . \quad . \quad (35)$$

whence $$x + y = \frac{b + 2c}{c - a} \cdot a \quad . \quad . \quad . \quad . \quad (36)$$

Substituting (36) in the second equation of (35) and solving for x/y we obtain

$$\frac{x}{y} = \frac{Z_2'}{Z_2''} = \frac{2a + b}{2(c - a)} \pm \sqrt{\left[\left\{\frac{2a + b}{2(c - a)}\right\}^2 - 1\right]} \quad (37)$$

which may be re-written as

$$e^k = -\frac{Z_1 + 2Z_2}{2(j\omega M - Z_2)} \mp \sqrt{\left[\left\{\frac{Z_1 + 2Z_2}{2(j\omega M - Z_2)}\right\}^2 - 1\right]} \quad (38)$$

or $$k = \text{arc cosh}\,\frac{Z_1 + 2Z_2}{2(j\omega M - Z_2)} \quad . \quad . \quad . \quad (39)$$

For any values of Z_1, Z_2 and M the attenuation may be calculated by the method indicated in equations (22) to (25).

Characteristics of various filters.—For the present, long or non-reflective lines only will be considered.

Equation (38) may be written in the form

$$e^k = x \mp \sqrt{(x^2 - 1)} \quad . \quad . \quad . \quad (40)$$

where x is in general a complex quantity (because of resistance). If x is complex, e^k must be complex and, between sections, there must be both change of amplitude and change of phase. Usually, however, the resistance will be small: the circuits become particularly interesting when the resistance is negligible. In this case x is real. If $x > 1$, e^k is wholly real and there is no change of phase (except possibly to antiphase, which may be considered to be a change of amplitude) between sections; the change is wholly one of amplitude. If $x < 1$ we may write

$$e^k = x \mp j\sqrt{(1 - x^2)} \quad . \quad . \quad . \quad (41)$$

showing that the general attenuation per section consists entirely in a phase change of magnitude arc cos x between sections, there being no change of amplitude.

Assuming that both Z_1 and Z_2 are single impedances, neither possessing both positive and negative reactance, then x must increase or decrease continuously, as the frequency changes. Change of amplitude can, therefore, only occur on *one* side of a definite cut-off frequency. Change of phase can only occur on the *other* side of the same frequency.

This point has already been illustrated in the case of the "low-pass" and "high-pass" filters having no resistance. Figs. 4 and 6 show this point of cut-off

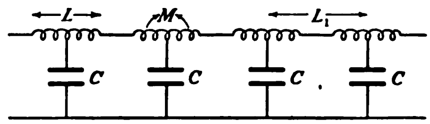

FIG. 9.

and also the manner in which practical conditions deviate from the ideal when the circuits have resistance.

If we consider the recurrent circuit of Fig. 9 it is clear that in a general way its characteristics will be similar to those of the "low-pass" filter of Fig. 3. There will be no reduction of amplitude until a definite cut-off frequency is attained. The circuit, however, becomes of particular interest when we may consider the loading coils to have no leakage. If the inductance of each is L we have the inductance per section

$$L_1 = \tfrac{1}{2}L \quad . \quad . \quad . \quad . \quad . \quad (42)$$

and $$M = \tfrac{1}{4}L \quad . \quad . \quad . \quad . \quad . \quad (43)$$

Substituting these values in (38) we find that it reduces to the form of (41), where

$$x = \frac{4 - \omega^2 LC}{4 + \omega^2 LC} \quad . \quad . \quad . \quad . \quad (44)$$

This expression is numerically always less than unity and hence there is no amplitude attenuation at any frequency. All frequencies are transmitted equally well. Such a circuit does not act as a filter at all. An examination of (44) shows, however, that so long as $\omega^2 LC$ is fairly small the phase change per section is proportional to the frequency, or the time-lag is constant.

In short lines, which are reflective, amplitude change between sections must occur, even though the numerical value of e^k is unity. For, in this case, the current in each section is made up of two numerically constant components the relative phase of which changes by an amount 2 arc cos x between one section and the next. The current in a section may therefore have any value between $[A]_{num.} + [B]_{num.}$ and $[A]_{num.} - [B]_{num.}$.

If instead of considering successive sections we fix our attention upon one particular section, and imagine the frequency to increase progressively, it is clear that the magnitude of the current will pass through a series of variations of a similar nature. Certain frequencies will therefore be transmitted with undue prominence. It is, however, possible to render the line sensibly non-reflective over the most important part of the range of transmissible frequencies; this type of distortion then practically disappears.

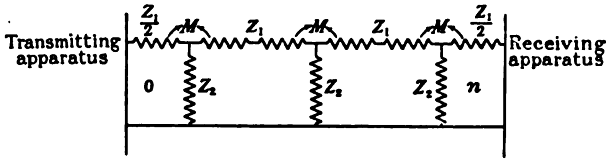

FIG. 10.

Initial sending-end (or surge) impedance. Non-reflective lines.—The initial sending-end impedance Z_0 is defined as that impedance by which the line, imagined long or non-reflective, can be replaced without changing the current in the zero section. The completed general line is shown in Fig. 10; Fig. 11 shows the line resolved (see also Fig. 8). It is clear that if the line is long or non-reflective the initial sending-end impedance is that included between the points X and Y, and we have

$$Z_0 = \tfrac{1}{2}Z_1 + j\omega M e^k + Z_2(1 - e^k) \quad . \quad . \quad (45)$$

or, substituting from (38),

$$Z_0 = \sqrt{\{(\tfrac{1}{2}Z_1 + Z_2)^2 - (j\omega M - Z_2)^2\}} \quad . \quad (46)$$

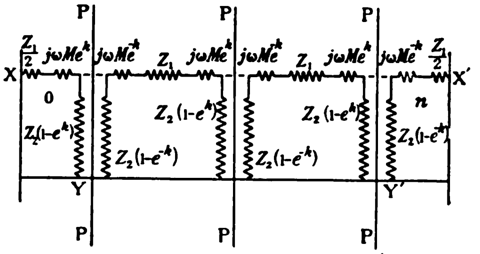

FIG. 11.

Since the line would be non-reflective if everything to the right of any line such as PP (Fig. 11) were removed, it will be equally non-reflective if an impedance

$$Z_R = Z_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

be connected between the points X', Y'. This is, therefore, the necessary condition for non-reflection at the receiving end.

If this condition could be fulfilled over the whole range of transmissible frequencies no undue prominence would be given by the *line* to any particular frequency (neglecting the small progressive change due to line resistance). The matter cannot, however, be so simply dismissed. An examination of (46) shows that for a line without resistance, Z_0 is of the nature of a pure resistance, over the range of frequencies transmitted. For a line having resistance its value approximates to a pure resistance. In any case, however, its magnitude is a function of the frequency, becoming zero (or nearly zero) at the point of cut-off.

All that it is possible to do, therefore, is to select a value for Z_R which shall be equal to Z_0 in the middle of the most important band of frequencies. Then over a considerable range the line will be sensibly non-reflective.

For instance, for the low-pass filter of no resistance (Fig. 3)

$$Z_0 = \sqrt{[(L/C) - (\omega^2 L^2/4)]} \quad . \quad . \quad . \quad (48)$$

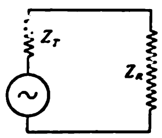

FIG. 12.

At the point of cut-off ω is $2/\sqrt{(LC)}$ and Z_0 is zero. Its value is $\sqrt{(L/C)}$ for low frequencies.

Undue prominence may also be given to particular frequencies by incorrect choice of the impedance of the transmitting apparatus. If the line is rendered practically free from distortion the current in the receiving section will bear an approximately constant ratio to the current in the transmitting section. It is necessary that this current in the transmitting section should be more or less independent of frequency. If

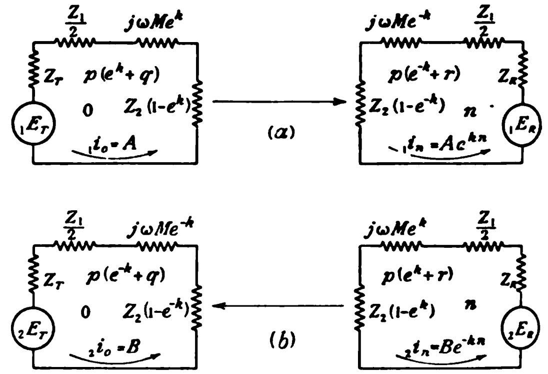

FIG. 13.

we assume that Z_R has been made equal to Z_0, the zero section may be represented by Fig. 12. It is then seen that the necessary condition is that $Z_T + Z_R$ should approximate as closely as possible to a pure resistance.

For maximum current transmitted $Z_T + Z_R$ should be as small as possible.

The general solution for a reflective line.—We have already considered the possibility of making the receiving section of the line non-reflective by adjustment of the receiver impedance. We may, however, imagine the same result effected by a source of potential inserted in the final section to supply the current through the impedance which actually exists.

For a potential ${}_1E_T$ in the zero section, transmitting to the nth section, suppose that a potential ${}_1E_R$, in the nth section, makes the line non-reflective (Fig. 13*a*). Assume that these potentials are removed and that a

potential ${}_2E_R$ is inserted in the nth section, transmitting to the zero section. To make the line non-reflective a potential ${}_2E_T$ is inserted in the zero section (Fig. 13*b*).

If we write

$$\left.\begin{aligned} p &\equiv j\omega M - Z_2 \\ q &\equiv \frac{Z_T + \frac{1}{2}Z_1 + Z_2}{j\omega M - Z_2} \\ r &\equiv \frac{Z_R + \frac{1}{2}Z_1 + Z_2}{j\omega M - Z_2} \end{aligned}\right\} \quad . \quad . \quad . \quad (49)$$

then we have

$$\left.\begin{aligned} {}_1E_T &= Ap(e^k + q) \\ {}_1E_R &= Ap(e^{-k} + r)e^{kn} \\ {}_2E_T &= Bp(e^{-k} + q) \\ {}_2E_R &= Bp(e^k + r)e^{-kn} \end{aligned}\right\} \quad . \quad . \quad . \quad (50)$$

Actual reflective conditions are obtained by superposing these two transmissions, making

$$\left.\begin{aligned} {}_1E_T + {}_2E_T &= E_T \\ {}_1E_R + {}_2E_R &= E_R \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (51)$$

Suppose that $E_R = 0$, then we have

$$\left.\begin{aligned} Ae^{kn}(e^{-k} + r) + Be^{-kn}(e^k + r) &= 0 \\ A(e^k + q) + B(e^{-k} + q) &= E/p \end{aligned}\right\} \quad . \quad (52)$$

Let us write

$$X \equiv \frac{e^k + q}{e^{-k} + q}, \quad Y \equiv \frac{e^k + r}{e^{-k} + r} \quad . \quad . \quad (53)$$

giving us

$$\left.\begin{aligned} AX + B &= \frac{E}{p(e^{-k} + q)} \\ Ae^{kn} + Be^{-kn}Y &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad (54)$$

or

$$\left.\begin{aligned} B &= \frac{E}{p(e^{-k} + q)(1 - e^{-2kn}XY)} \\ A &= \frac{-Ye^{-2kn}E}{p(e^{-k} + q)(1 - e^{-2kn}XY)} \end{aligned}\right\} \quad . \quad . \quad (55)$$

The following transformations are of value. From equation (33) and Fig. 8 we have

$$(j\omega M - Z_2)(e^k + e^{-k}) + Z_1 + 2Z_2 = 0 \quad . \quad (56)$$

or

$$\frac{\frac{1}{2}Z_1 + Z_2}{j\omega M - Z_2} = -\frac{e^k + e^{-k}}{2} \quad . \quad . \quad . \quad (57)$$

giving us

$$\left.\begin{aligned} q &= \frac{Z_T}{p} - \frac{e^k + e^{-k}}{2} \\ r &= \frac{Z_R}{p} - \frac{e^k + e^{-k}}{2} \end{aligned}\right\} \quad . \quad . \quad . \quad (58)$$

whence

$$\left.\begin{aligned} X &= \frac{2Z_T + p(e^k - e^{-k})}{2Z_T - p(e^k - e^{-k})} \\ Y &= \frac{2Z_R + p(e^k - e^{-k})}{2Z_R - p(e^k - e^{-k})} \end{aligned}\right\} \quad . \quad . \quad . \quad (59)$$

When the attenuation becomes great the values of A and B reduce to

$$\left.\begin{aligned} A &= \frac{2E}{2Z_T + p(e^k - e^{-k})} \\ B &= -\frac{e^{2kn}}{Y} \cdot \frac{2E}{2Z_T + p(e^k - e^{-k})} \end{aligned}\right\} \quad . \quad (60)$$

Selective transmission of particular frequencies.—Reference has already been made to the fact that in a reflective line particular frequencies may transmit with undue prominence. This can be clearly seen from the quantities just deduced. Let us consider a filter having no resistance, the impedances Z_T and Z_R being negligible. In this case the distortion is exaggerated, but the assumption enables us to examine the nature of the phenomenon easily.

For this case

$$X = -1, \; Y = -1, \; q = -\tfrac{1}{2}(e^k + e^{-k}) = r \quad . \quad (61)$$

$$e^{-k} + q = \tfrac{1}{2}(e^{-k} - e^k) \quad . \quad . \quad . \quad (62)$$

$$\left.\begin{aligned} A &= \frac{2e^{-2kn}}{p(e^{-k} - e^k)(1 - e^{-2kn})}E \\ B &= \frac{2}{p(e^{-k} - e^k)(1 - e^{-2kn})}E \end{aligned}\right\} \quad . \quad . \quad (63)$$

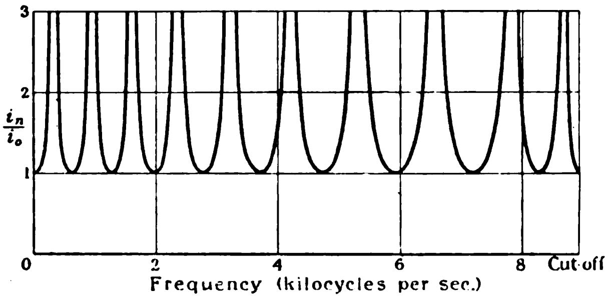

FIG. 14.

The transmitted current

$$i_0 = \frac{2E}{p(e^{-k} - e^k)} \cdot \frac{1 + e^{-2kn}}{1 - e^{-2kn}} \quad . \quad . \quad (64)$$

The received current

$$i_n = \frac{2E}{p(e^{-k} - e^k)} \cdot \frac{2e^{-kn}}{1 - e^{-2kn}} \quad . \quad . \quad (65)$$

$$\therefore \frac{i_n}{i_0} = \frac{2e^{-kn}}{1 + e^{-2kn}} = \frac{2}{e^{kn} + e^{-kn}} \quad . \quad . \quad (66)$$

This may be written

$$\left.\begin{aligned} \frac{i_n}{i_0} &= \sec n\alpha \\ \text{where} \quad e^k &\equiv \cos\alpha + j\sin\alpha \end{aligned}\right\} \quad . \quad . \quad . \quad (67)$$

(we are only considering the case where the numerical value of e^k is unity).

From one end of the frequency scale to the point of cut-off, α changes from 0 to π. Hence $n\alpha$ changes by an angle π as many times as there are sections in the line. Fig. 14 shows a rough graph of this ratio for a low-pass filter of 10 sections, having no resistance and cutting off at about $\omega = 8\,900$.

APPENDIX.

Solution of a General Case.

The quantities chosen in the following example are intended to be illustrative rather than practical. The circuit is that of Fig. 10. The chokes are assumed to have considerable leakage, so that an approximate cut-off is obtained within the practical range of frequencies. The line is supposed to consist of 10 sections. The constants of the circuit are :—

$$L = 0\cdot5\text{H},\ M = 0\cdot1\text{H},$$

whence $L_1 = 0\cdot3\text{H}$, $C = 0\cdot5 \times 10^{-6}\text{ F}$, $R_1 = 100$ ohms, $Z_T = Z_R = 1\,000$ ohms, $n = 10$.

Beyond the point of cut-off ($\omega = 8\,944$) the approximate expressions (60) may be used. As far as the transmitted current is concerned B is negligible after cut-off, but it naturally contributes a substantial fraction of the received current.

The received current is determined as follows :—

$$i_n = Ae^{kn} + Be^{-kn} \quad . \quad . \quad . \quad . \quad (68)$$

Substituting from (54) we obtain

$$i_n = Ae^{kn}\left(\frac{Y-1}{Y}\right) \quad . \quad . \quad . \quad . \quad (69)$$

If only the amplitude of the current is required we may write

$$[i_n]_{num.} = [A]\,[e^{kn}]\left[\frac{Y-1}{Y}\right] \quad . \quad . \quad (70)$$

The method and order of working are clear from Tables 1 to 5. The effect of reflection is clearly seen, although it is limited.

Table 1.

ω	e^k	e^{-k}	p	$p(e^k - e^{-k})$	e^{-20k}
2 000	0·5536 − 0·7720j	0·6130 + 0·8554j	1 200j	1 953 − 71·3j	2·760 + 0·3429j
4 000	− 0·1055 − 0·9398j	− 0·1167 + 1·0510j	900j	1 792 + 10·1j	− 1·638 + 2·702j
6 000	− 0·5682 − 0·7437j	− 0·6460 + 0·8509j	933j	1 488 + 72·8j	3·325 + 1·741j
8 000	− 0·8068 − 0·3920j	− 1·0028 + 0·4872j	1 050j	933·2 + 205·8j	− 8·168 − 3·289j
10 000	− 0·6566 − 0·0638j	− 1·5110 + 0·1472j	1 200j	253·2 + 1 026j	Very large
12 000	− 0·5383 − 0·0300j	− 1·8519 + 0·1032j	1 367j	182·1 + 1 795j	
14 000	− 0·4869 − 0·0203j	− 2·0501 + 0·0859j	1 543j	163·8 + 2 412j	
16 000	− 0·4583 − 0·0154j	− 2·1793 + 0·0734j	1 725j	153·2 + 2 969j	
18 000	− 0·4405 − 0·0125j	− 2·2689 + 0·0649j	1 911j	147·9 + 3 494j	
20 000	− 0·4283 − 0·0107j	− 2·3337 + 0·0583j	2 100j	144·9 + 4 001j	

Table 2.

ω	$p(e^k + q)$	$p(e^{-k} + q)$	$X = Y$	Approximate values of A/B. (Not to be used below $\omega = 8\,000$) mA/V
2 000	1 976 − 35·65j	24 + 35·65j	24·78 − 39·10j	0·5059 + 0·00913j
4 000	1 896 + 5·05j	104 − 5·05j	18·18 + 0·9533j	0·5273 − 0·00140j
6 000	1 744 + 36·4j	256 − 36·4j	6·659 + 1·089j	0·5731 − 0·01196j
8 000	1 462 + 102·9j	538 − 102·9j	2·584 + 0·6850j	0·6807 − 0·04791j
10 000	1 127 + 513·0j	873 − 513·0j	0·7066 + 1·002j	0·7347 − 0·3344j
12 000	1 091 + 897·5j	909 − 897·5j	0·1141 + 1·100j	0·5466 − 0·4495j
14 000	1 082 + 1 206j	918 − 1 206j	− 0·2008 + 1·050j	0·4121 − 0·4592j
16 000	1 077 + 1 484j	923 − 1 484j	− 0·3957 + 0·9716j	0·3203 − 0·4414j
18 000	1 074 + 1 747j	926 − 1 747j	− 0·5263 + 0·8940j	0·2554 − 0·4155j
20 000	1 072 + 2 000j	928 − 2 000j	− 0·6185 + 0·8226j	0·2082 − 0·3884j

Table 3.

ω	XY	$1 - e^{-20k}XY$	$e^{-20k}Y$	$p(e^{-k}+q)(1 - e^{-20k}XY)$
2 000	− 914·8 − 1 938j	1 861 + 5 663j	81·75 − 99·43j	− 157 200 + 202 200j
4 000	329·7 + 34·64j	634·7 − 834·1j	− 32·37 + 47·58j	61 800 − 89 950j
6 000	43·16 + 14·50j	− 117·2 − 123·3j	20·24 + 15·21j	− 34 490 − 27 300j
8 000	6·208 + 3·540j	40·06 + 49·33j	− 18·85 − 14·09j	26 630 + 22 420j

TABLE 4.

ω	B/E	$A/E = -Ye^{-20k}B$	A/E (From previous columns and Tables)	$(A+B)/E$
	mA/V	mA/V	mA/V	mA/V
2 000	$-0{\cdot}002396 - 0{\cdot}003083j$	$0{\cdot}5025 + 0{\cdot}01376j$	$0{\cdot}5025 + 0{\cdot}01376j$	$0{\cdot}5001 + 0{\cdot}01068j$
4 000	$0{\cdot}005189 + 0{\cdot}007552j$	$0{\cdot}5273 - 0{\cdot}00243j$	$0{\cdot}5273 - 0{\cdot}00243j$	$0{\cdot}5325 + 0{\cdot}00512j$
6 000	$-0{\cdot}01782 + 0{\cdot}01411j$	$0{\cdot}5753 - 0{\cdot}01457j$	$0{\cdot}5753 - 0{\cdot}01457j$	$0{\cdot}5575 - 0{\cdot}00046j$
8 000	$0{\cdot}02197 - 0{\cdot}01850j$	$0{\cdot}6748 - 0{\cdot}0391j$	$0{\cdot}6748 - 0{\cdot}0391j$	$0{\cdot}6968 - 0{\cdot}0576j$
10 000			$0{\cdot}7347 - 0{\cdot}3344j$	$0{\cdot}7347 - 0{\cdot}3344j$
12 000			$0{\cdot}5466 - 0{\cdot}4495j$	$0{\cdot}5466 - 0{\cdot}4495j$
14 000			$0{\cdot}4121 - 0{\cdot}4592j$	$0{\cdot}4121 - 0{\cdot}4592j$
16 000			$0{\cdot}3203 - 0{\cdot}4414j$	$0{\cdot}3203 - 0{\cdot}4414j$
18 000			$0{\cdot}2554 - 0{\cdot}4155j$	$0{\cdot}2554 - 0{\cdot}4155j$
20 000			$0{\cdot}2082 - 0{\cdot}3884j$	$0{\cdot}2082 - 0{\cdot}3884j$

TABLE 5.

ω	$\left[\frac{Y-1}{Y}\right]$	$[e^{10k}]$	$[A/E]$	Transmitted current $[A+B]/E$	Received current
			mA/V	mA/V	mA/V
2 000	0·9678	0·5996	0·5027	0·5002	0·2917
4 000	0·9451	0·5720	0·5273	0·5325	0·2851
6 000	0·8541	0·5162	0·5755	0·5575	0·2536
8 000	0·6456	0·3370	0·6759	0·6992	0·1470
10 000	0·8513	0·01544	0·8074	0·8074	0·0106
12 000	1·277	0·002076	0·7077	0·7077	0·0019
14 000	1·492	0·0007562	0·6172	0·6172	0·0007
16 000	1·621	0·0004192	0·5453	0·5453	0·0004
18 000	1·705	0·0002762	0·4876	0·4876	0·0002
20 000	1·756	0·0002081	0·4407	0·4407	0·0002

THE ATTENUATION OF WIRELESS WAVES DUE TO THE RESISTANCE OF THE EARTH.*

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[Communicated by peımission of the Radio Research Board.]

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SUMMARY.

The paper calls attention to the present condition of knowledge on the subject of the attenuation of wireless waves travelling over the earth's surface, due to energy absorption by the earth itself. The theories put forward on this problem by Sommerfeld and Zenneck are briefly outlined, and it is shown that the latter has taken account only of a special case of the more general theory of Sommerfeld. The results deduced from this theory have been worked out for some typical practical cases of both short- and long-wave transmission, but, owing to the complete lack of experimental evidence, no practical test of the theory has yet been made. In view of the importance of a knowledge of ground absorption in connection with the complete study of the propagation of wireless waves of all lengths over the earth's surface, it is highly desirable that a systematic experimental investigation should be carried out in the near future.

(1) SCOPE OF THE PAPER.

During recent years the problem of the propagation of wireless waves over the earth's surface has been attacked by several experimenters by the systematic measurement of the intensity and direction of the fields arriving at a receiver from a distant transmitting station. The results of this research show generally that two series of waves arrive at the receiving station from the transmitter. The first of these is the "direct" wave which is propagated along the surface of the earth following its curvature by diffraction. The second series comprises those "indirect" waves which have travelled by way of the upper regions of the atmosphere, having reached the receiver by one or more suitable deflections. In a complete study of the problem it is evidently very desirable to ascertain what are the relative contributions of the direct and indirect waves to the resultant field strength under all practical conditions of wireless transmission over the earth's surface; and, further, to account on satisfactory theoretical grounds for all the experimental results obtained.

The complete problem may be conveniently divided into two parts: first, that of determining the field strength at distances from the transmitter so great that the curvature of the earth has to be taken into account; and second, that of determining this quantity at points relatively close to the receiver, i.e. over distances for which the earth may be considered flat. The first part of the problem has proved to be of greater interest in the past and has accordingly had a great deal of attention paid to it. This has probably been due to the fact that within the range of wave-lengths to which commercial communication has been restricted in the past, no difficulty was experienced in obtaining satisfactory transmission over distances which come within the second category. Within this region it is evident that the direct wave will appreciably contribute to the resultant field strength, and it is thus important to have an exact knowledge of the extent to which this wave is attenuated due to the finite conductivity of the earth. This question is becoming more important with the use of shorter wave-lengths, and cases are already on record in which the direct wave has become too weak for detection or measurement at distances much less than those at which the indirect wave has become the sole contributor to the field at the earth's surface. For example, in some observations published by A. H. Taylor,* it has been shown that for wave-lengths of 40 metres and less, and with a given power, the maximum range of transmission directly along the earth's surface was less than 100 miles, and that no signals could be received at greater ranges until a distance exceeding 400 miles was reached. At these greater distances the signals were evidently due to the reception of waves from the upper atmosphere. The intervening range in which neither the direct nor the downcoming waves can be received is commonly referred to as the "jump over" or "skipped distance."

This attenuation problem has been studied theoretically by Sommerfeld † and Zenneck ‡, but as far as the authors are aware the formulæ which they obtained have never been experimentally tested. In Sommerfeld's work, results were obtained which can be employed for the calculation of attenuation over a very large range of wave-lengths, including the shorter waves which are now coming into practical use and on which the matter has assumed greatly increased importance. Owing to the lack of experimental data upon the subject, an investigation has been planned and will be carried out as soon as opportunity permits. Pending the results of this, it has been considered useful to give a brief outline of Sommerfeld's work, together with a series

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* A. H. TAYLOR: "An Investigation of Transmission on the Higher Radio Frequencies," *Proceedings of the Institute of Radio Engineers*, 1925, vol. 13, p. 677. Also A. H. TAYLOR and E. O. HULBURT: "Wave Propagation at High Frequencies," *Q.S.T.*, 1925, vol. 9, p. 12.

† A. SOMMERFELD: "On the Spreading of Waves in Wireless Telegraphy," *Annalen der Physik*, 1909, vol. 28, p. 665.

‡ J. ZENNECK: "The Propagation of Plane Electromagnetic Waves along a Plane Conducting Surface and its Bearing on Wireless Telegraphy," *ibid.*, 1907, vol. 23, p. 846.

of attenuation curves calculated for such cases as are of interest.

(2) Outline of Sommerfeld's Theory.

Given a Hertzian oscillator situated on the earth's surface, Sommerfeld obtains an expression for the intensity of the field at any other point on the earth, taking into account the conductivity and dielectric constant of the ground. Throughout his work he neglects the effect of the curvature of the earth and assumes the atmosphere to be homogeneous. (It may be pointed out here that Duddell and Taylor's experimental results for transmission oversea, as mentioned on page 769, show that the effect of the curvature of the earth up to a distance of 60 miles is practically negligible.) The formulæ obtained by Sommerfeld, which are most suitable for numerical calculation, are simplified by assuming $2\sigma/f$ to be much greater than unity, where σ is the conductivity of the earth in electrostatic units, and f is the frequency corresponding to the waves. Taking the accepted value of σ as 10^8 * for land in this country, then $2\sigma/f$ will exceed 10 for all wave-lengths above 15 metres, and so this assumption is applicable to almost the entire range of practical cases.

The notation employed for this résumé is as follows :— Principal axes are assumed with the transmitter at the origin and Ox the direction of transmission.

K = dielectric constant of the earth,
σ = conductivity of the earth,
f = frequency,
$j = \sqrt{(-1)}$
$K' = K - (j2\sigma/f)$
$\mu = \sqrt{K'}$ = " refractive index " of the earth,
P = vector potential = distance rate of change of the radiated magnetic field = $\partial H/\partial x$.

$$\rho = \frac{\pi}{\mu^2} \cdot \frac{x}{\lambda} = \text{" numerical distance."}$$

Beginning with the classical equations of Clerk Maxwell and applying boundary conditions, Sommerfeld obtains a series for P which is finally reduced to forms suitable for calculation. The approximate solutions differ according to whether the numerical distance ρ is large or small.

(a) If ρ is large, say, not less than 10, then the following equation applies :—

$$P = -\left\{\frac{1}{2\rho} + \frac{1\,.\,3}{2\,.\,2\rho^2} + \frac{1\,.\,3\,.\,5}{2\,.\,2\,.\,2\rho^3} + \ldots\right\}\frac{e^{j2\pi x/\lambda}}{x} \qquad (1)$$

When ρ is very large this reduces to

$$P = \frac{A\lambda^2}{x^2} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

i.e. for a given current in the oscillator the radiated field intensity is proportional to the square of the wave-length and inversely proportional to the square of the distance.

(b) If ρ is small, the approximate formula is as follows :—

$$P = (u - jv)\frac{e^{j2\pi x/\lambda}}{x} \quad . \quad . \quad . \quad . \qquad (3)$$

where $$u = 1 - \frac{2}{1}\rho + \frac{2\,.\,2}{1\,.\,3}\rho^2 - \frac{2\,.\,2\,.\,2}{1\,.\,3\,.\,5}\rho^3 + \ldots$$

and $$v = \sqrt{(\pi\rho)}e^{-\rho}$$

From formulæ (1) to (3) it is possible to calculate the intensity of the radiation field at any distance over which it can be assumed that the curvature of the earth produces no appreciable effect.

(3) Discussion of Calculations from Sommerfeld's Equations.

In Figs. 1 to 4 the values of the radiated field have been calculated for distances up to 150 km and for wave-lengths from 30 to 1 000 m. Graphs are given

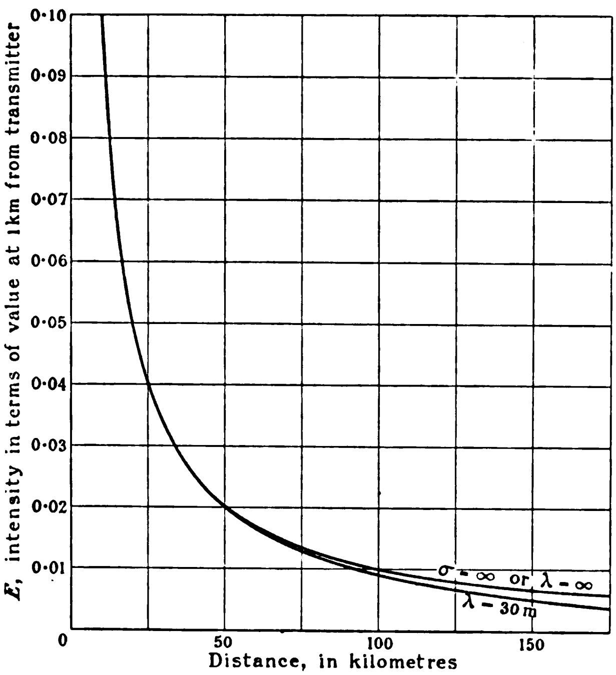

Fig. 1.—Attenuation over sea ($\sigma = 10^{10}$ E.S.U.).

for transmission over sea water (assuming $\sigma = 10^{10}$ E.S.U.*) and over land for which $\sigma = 10^8$ E.S.U.† In Figs. 1 and 2 the actual field intensity at various distances is shown in terms of the value at 1 km from the transmitter. In Figs. 3 and 4 the results are shown as the ratio of the intensity of the field which pertains for transmission over sea or land to the intensity which would be obtained if the earth were a perfect conductor.

In each of Figs. 1 to 4 a curve is given as applying to the condition $\lambda = \infty$ or $\sigma = \infty$. It is of course realized that in considering the radiated field intensity the minimum distance of the point under consideration from the transmitter is of the order of a wave-length. The above hypothetical curves are, however, inserted as showing the upper limits of the field intensity which could be obtained either by using very long wireless waves or by transmission over a perfectly conducting earth.

* This corresponds to approximately 10^{-13} in electromagnetic units, or to 10 000 ohms per cm cube.

* Equals approximately 10^{-11} in E.M.U., or 100 ohms per cm cube.
† Equals approximately 10^{-13} in E.M.U., or 10 000 ohms per cm cube.

(*a*) *Transmission over sea.*—Figs. 1 and 3 demonstrate very clearly that for wave-lengths above 100 m the attenuation over sea is practically identical with that

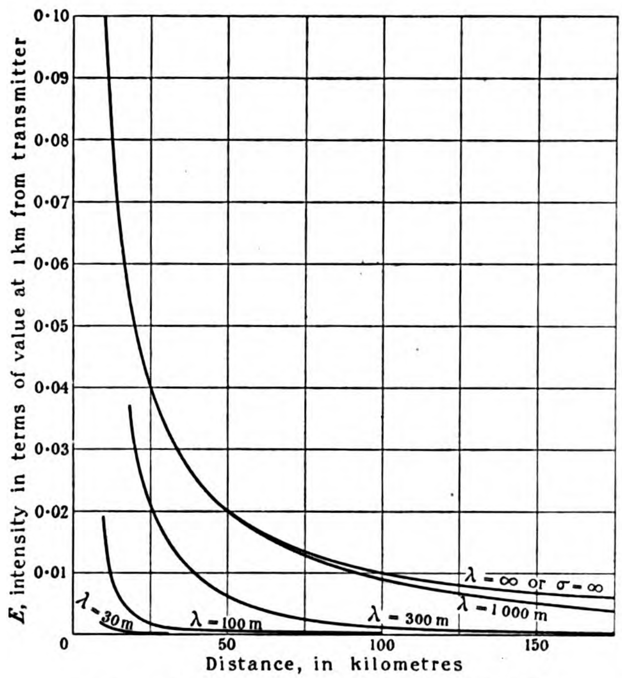

FIG. 2.—Attenuation over land ($\sigma = 10^8$ E.S.U.).

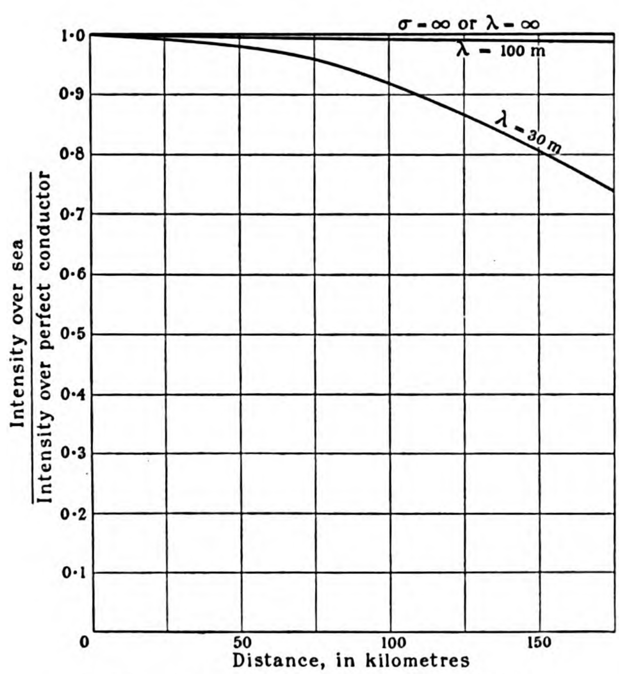

FIG. 3.—Attenuation over sea ($\sigma = 10^{10}$ E.S.U.).

which would hold for the ideal case of a perfect conductor, the field intensity decreasing inversely as the distance. With a wave-length of 30 m, however, a noticeable departure from the ideal case is observed, and at a distance of 150 km the field has fallen to about 0·8 of its ideal value.

(*b*) *Transmission over land.*—When the transmission is entirely over land the effect of the energy absorption due to the higher resistance is very marked on wave-lengths below 1 000 m, as shown in Figs. 2 and 4. The 1 000-m wave is attenuated over land to approximately the same extent as the 30-m wave over sea. On a wave-length of 300 m, however, the intensity at a distance of 150 km over land is only 0·08 of the ideal value or of its value for transmission over sea to the same distance. On the shorter wave-lengths the attenuation becomes still more marked. For example, on a wave-length of 30 m the intensity at only 10 km over land is reduced to 0·01 of its ideal or approximate

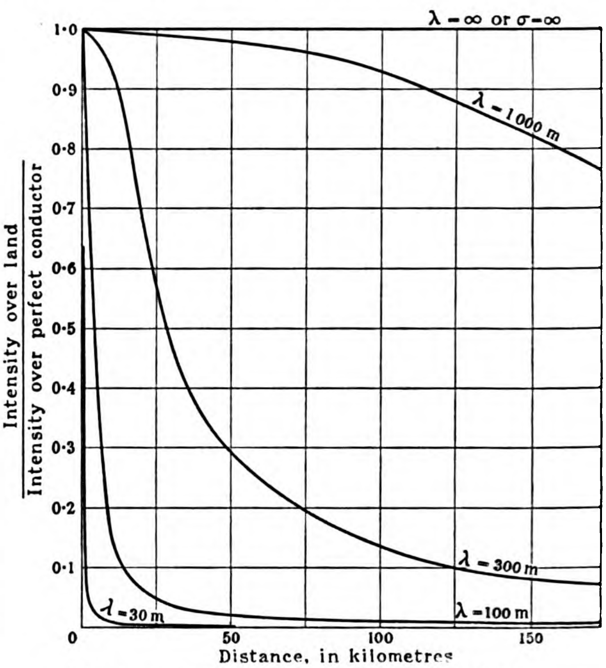

FIG. 4.—Attenuation over land ($\sigma = 10^8$ E.S.U.).

over-sea value, which is equivalent to 0·001 of the intensity at 1 km from the transmitter.

Such examples serve to illustrate very clearly the great disadvantage of the shorter wave-lengths for transmission over small and medium distances, at which the curvature of the earth and the effects of the upper atmosphere are negligible.

(4) ZENNECK'S ANALYSIS AS A PARTICULAR CASE OF SOMMERFELD'S THEORY.

In his analysis of the effect of the finite conductivity of the earth on wireless-wave propagation, Zenneck simplified the problem by making the assumption that at a large distance from the transmitter the wave may be considered plane, thereby neglecting the ordinary attenuation of the wave due to spreading. On this basis Zenneck showed that the decrease in intensity of the wave could be represented by an expression of the form

$$E = Be^{-ax} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where a is an attenuation constant depending upon the constants of the earth and the wave-lengths, viz. $a = \pi/(\mu^2\lambda)$. It is thus evident that the quantity ax is identical with Sommerfeld's ρ, and that this part of the attenuation is embodied in the value of v which forms part of equation (3) above. Under certain conditions when u approaches zero, equation (3) for the intensity takes the form of equation (4). Indeed, Sommerfeld pointed out this in his theoretical work and showed that this constituent part, which may be called "Zenneck's wave," is of the nature of a surface wave and that, apart from its attenuation due to earth resistance, the field intensity varies inversely as the square root of the distance.

It is clear, therefore, that Zenneck provided a partial solution which is valid only under particular conditions, while Sommerfeld's solution is quite general. Since Sommerfeld includes Zenneck's particular case, there would appear to be no point in making any calculations from the latter's formulæ. It is interesting, however, to ascertain under what conditions Zenneck's theory gives an approximate solution. This information is readily obtainable from Sommerfeld's theory and is recorded in Table 1.

TABLE 1.

Wave-length	Range of transmission over which equation (4) is valid	
	Over land ($\sigma = 10^8$)	Over sea ($\sigma = 10^{10}$)
m	km	km
10 000	10 000 to 32 000	Too large for practical use
3 000	900 to 3 100	Too large for practical use
1 000	100 to 320	Too large for practical use
300	9 to 31	9 800 to 29 000
100	1·0 to 3·1	1 100 to 3 300
30	0·09 to 0·3	98 to 290

This table shows that the applicability of Zenneck's solution is very limited. Thus on land and with a wave-length of 1 000 m and upwards it is never valid in the first 100 km; and at distances much larger than this the curvature of the earth would have to be taken into account and both Zenneck's and Sommerfeld's formulæ become invalid. For wave-lengths less than 1 000 m the range of validity over land is very small. Thus on 300 m it is only 22 km, and on 100 m it is only 2 km. For over-sea transmission the distances over which Zenneck's formula could be used are not small enough for the earth to be assumed plane for any wave-lengths above 30 m. It appears, therefore, that on nearly all wave-lengths at present in use for commercial purposes the conditions under which Zenneck's theory holds good are so limited as to render his formulæ of little value for practical purposes.

(5) PREVIOUS EXPERIMENTAL RESULTS.

As far as the authors have been able to ascertain, the only previously published papers which provide any reliable data upon the problem under discussion are those of Duddell and Taylor describing experiments made as long ago as 1905,* and of Bown and Gillett published in 1924.† It is significant of the lack of interest in this subject that apparently no investigation of it was carried out in the intervening 19 years.

The first of the above papers describes two sets of experiments, the first made over land in Bushy Park, Teddington, and the second over sea across the St. George's Channel. In both experiments a spark transmitter was used and was moved to various positions while the corresponding current in the receiving aerial was measured by means of a thermo-galvanometer. In the first series of experiments carried out in Bushy Park the range of transmission was quite small, never being greater than 7 500 ft. (2·25 km). Also the site of the experiments was far from uniform, the open grass spaces being interspersed among clumps of large trees of several hundred yards in extent. In view of these considerations and of the fact that the wave-length employed was 400 to 500 ft. (120 to 150 m), and of the probable serious effect of the trees on such short waves, it is not considered that the conditions of the experiments were such as to provide data sufficiently reliable for comparison with any theoretical formulæ. The experiments did, however, show quite clearly that the intensity of the waves decreased much more rapidly than the inverse distance from the transmitter, a fact which was probably due to absorption of energy by the ground and trees.

The second series of experiments of Duddell and Taylor were much more satisfactory, being carried out over an open-sea path at distances up to 60 miles (96 km). The wave-length employed is not stated, but was probably of the same order as above. Under these conditions the results of the measurements showed that the received current and, thus, the field intensity of the waves were practically inversely proportional to the distance, as would be the case for uniform spreading over a plane perfect conductor. The product of received current and distance did show a steady but small decrease over the range of transmission. This decrease represents the sum of that corresponding to the small attenuation of such waves when transmitted over sea-water, as indicated from the theoretical curve in Fig. 3, and the decrease which would be caused by the slight but appreciable curvature of the earth over a distance of 100 km.

In Bown and Gillett's experiments it is perhaps natural to find that the conditions were a little more satisfactory. The measurements were made with a portable coil receiver on the undamped-wave transmissions from broadcasting stations in New York and Washington, U.S.A. In the paper referred to the results are well represented both in the form of curves showing the decrease of field strength with distance, and as contour maps giving the curve of uniform field distribution round the transmitting station. On the wave-length of 469 m employed, these results show very clearly that the attenuation is small over river water and increasingly greater for moist grass-land and dry sandy soil. The experiments also clearly demonstrate

* W. DUDDELL and J. E. TAYLOR: "Wireless Telegraphy Measurements," *Journal I.E.E.*, 1905, vol. 35, p. 321.

† R. BOWN and G. D. GILLETT: "Distribution of Radio Waves from Broadcasting Stations over City Districts," *Proceedings of the Institute of Radio Engineers*, 1924, vol. 12, p. 395.

the high absorption which is experienced when the transmission is over tall iron-frame buildings as in the New York City area.

By dissecting the curves for the different natures of the path of transmission, Bown and Gillett compared the measured results with the well-known Austin-Cohen transmission formula, which is as follows :—

$$\text{Field strength} = \left\{ 377 \frac{h_s I_s}{\lambda x} \right\} e^{-\alpha x/\sqrt{\lambda}} \text{ microvolts per metre} \quad . \quad (5)$$

where h_s = effective height of the transmitting aerial in metres ;

I_s = transmitting aerial current in amperes ;

λ = wave-length in km ;

x = distance in km.

The attenuation due to resistance absorption is expressed by the quantity $e^{-\alpha x/\sqrt{\lambda}}$ and the measured values of α are given in the paper as :—

0·028 for dry sandy soil,
0·009 for moist soil,
0·0025 for water,

while the value of 0·0015 is commonly used in the above formula for over-sea transmission in daylight. As this attenuation formula is of an empirical nature, however, and, further, as it needs verification for other wave-lengths, it is not of much value in making comparisons with the theoretical formulæ discussed in Sections (2) and (3). Furthermore, the fact that the measurements were made over ranges which comprised patches of soil of a varying nature, of which no information was obtained as to the effective conductivity, would also make a direct comparison with theory very difficult.

(6) Conclusions.

In this paper the authors have thus arrived at the conclusion that for wireless-wave transmission over comparatively short distances under conditions where it is necessary to take into account the resistance of the earth, Sommerfeld's analysis alone leads to a means of calculating the attenuation for all practical cases. The graphs in the paper provide in summarized form the practical information to be derived from this theory. Owing to the complete lack of experimental evidence on the subject, it is as yet impossible to state whether the theoretical values are in accordance with those obtained in practice.

It is evident that what is wanted is a series of careful measurements giving either the absolute or the comparative field strengths at different distances up to say 50 or 100 km, the transmission being made over ground as uniform as possible, the conductivity of this ground having been measured by an independent method such as has already been employed in England.* It will, of course, be a condition of these measurements that any waves received from the upper atmosphere have no perceptible effect.

* R. L. Smith-Rose and R. H. Barfield: "On the Determination of the Directions of the Forces in Wireless Waves at the Earth's Surface," *Proceedings of the Royal Society*, A, 1925, vol. 107, p. 587.

DISCUSSION ON

"DIELECTRIC PROBLEMS IN HIGH-VOLTAGE CABLES." *

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 15 FEBRUARY, 1926.

Mr. W. P. Fuller: The paper seems to show how very much we are in the dark with regard to the behaviour of dielectrics when it becomes necessary to use a formula with two supposed constants which are actually functions of time. As the author states, liquid dielectrics also show absorption and it is difficult to imagine systems of capacities and resistances, having different time constants, in a liquid. I think that something more fundamental than Maxwell's conception is required, and that we shall have to go to the atom to find a satisfactory explanation. The " V " curve seems to be characteristic not only of a cable but of its constituents. Some cable compounds give a " V " curve, and some do not, at any rate above 15° C. The characteristic is to be found in dry paper alone, and the curve obtained with a cable is a resultant depending on the constituent parts and on their distribution. Hence for given materials the relationship between the losses at different frequencies will depend on the proportion of oil in series with the paper fibres and the proportion in parallel, and, due to the same causes, the d.c. conduction cannot be used as a basis to deduce the a.c. loss. I am inclined to agree with the author's explanation in Section (IX) of the cause of cable breakdown, namely, that there is a deflection of the electric field in a direction parallel to the fibres due to contact effects, although the difference of contact in various parts can be only a few mils and it is difficult to see how this alone can cause a considerable field displacement.

Mr. E. L. Morland: Dielectric problems in high-voltage cables for pressures between 20 kV and 66 kV are still, unfortunately, a subject of research, and the need for reliable super-tension cable is, I am afraid, ahead of cable development. The air pockets in the impregnating medium, which at voltages up to 20 kV may not be detrimental, present a difficult dielectric problem when the voltage is above that figure. Chemical changes resulting in breakdown may occur slowly or quickly, in accordance with the condition of the dielectric, at different hot spots which are, I think, due to air entrapped during the process of manufacture and occasionally while jointing is in progress. Generally, the condition of charring takes, I think, some time for breakdown to occur, and is not affected by transient surges. This condition of entrapped air would seem to point to a radical change in the design, and possibly one solution may lie with an impregnating fluid which, owing to its nature, does not result in a cable which is unstable under working conditions, and which yet allows a more complete disturbance of the air voids each time the cable is heated under load and cooled off. This would tend to prevent oxidation and the forming and charring of leakage paths, which result in complete puncture and failure. Tests taken on sample lengths of cable, heated and cooled many times, over a range of temperature between 65° F. and 140° F., should show after each test very slight variation in the dielectric power factor of the cable, which, complying with the conditions I have mentioned, is not subject to the progressive deterioration at present met with.

Mr. P. J. Robinson: Can the author say whether any experiments have been carried out with paper impregnated with de-aerated oil, and whether samples of paper impregnated in the ordinary way have been compared from an electrical pressure point of view with samples of paper impregnated with de-aerated oil, and if so with what results? Quite recently I carried out some experiments in connection with the de-aeration of water and I thought that by covering the surface of the de-aerated water with a heavy mineral oil I could keep the air from mixing with it, but in a relatively short time the air had passed through the oil and the water was appreciably aerated. I mention this as a matter of interest, and as a lead-sheathed cable excludes all free air from entering the cable the author's opinion of de-aeration will be of considerable interest. What precautions are taken in hilly districts to avoid big pressures due to static head? Obviously, whether the insulating material is fluid or semi-plastic, it will drain to the lowest point and create a pressure there which is dependent on the head due to the elevation of the hill. Also, if precautions are taken, what head does the author consider should be fixed upon as a maximum allowable? It is obvious that any draining to one point which may be bulged owing to heating and cooling or pressure due to head will create a space at the highest point of the cable which will be under vacuum or partial vacuum conditions, in which case some of the air will be drawn from the oil by the partial vacuum so created and will create a weak spot. It would be interesting to know whether any attempt has been made in the manufacture of the cable to drive out as much air as possible by heating the cable to a temperature at which it will normally operate, as this will then allow of less free air being driven off when the cable is in service due to normal heating. Further, have any tests been made to show whether the air of absorption is freed by electrical tension? The paper refers to tests on cable only, and it is suggested that separate lengths should be cut from the cable and tested out, but as most of the trouble experienced has been in the joints it would appear essential to test the whole cable when laid, in order rigorously to prove the efficiency of the joints. It would be interesting to know how many points of a curve were taken when the models shown on the table were constructed.

Mr. C. R. Bolton: When describing the three-dimension graph models, the author mentioned that one, having obviously the worst characteristics, represented the test-results obtained from an experimental

* Paper by Mr. P. Dunsheath (see page 97).

cable built with a type of paper which at one time was considered to be the best for cable making. Does he refer to an all-manila paper, and, if so, what are the particular properties of this paper which are now found to be unsuitable? For example, has the author found it difficult to dry it thoroughly?

Mr. J. H. Collie: Can the author give any idea of the appreciable loss that takes place in a network of mains due to leakage through the dielectric, and whether these losses vary to any extent as between concentric, three-core, and single-core cables? He mentions that the leakage loss is greater in a.c. than in d.c. cables, so I presume that the loss on a given length of d.c. feeder cable is less than it would be on an a.c. cable. With regard to the question of stressing cables during testing, have the cable makers given any indication as to what they consider to be a safe, suitable testing pressure?

Mr. P. W. Cave: With reference to the cause of breakdown in the single-core cable, the author mentions that the charring may be due to heating or ionization. I suggest that it is a combination of the two, and that ionization is the predominating feature. It is comparatively easy to exclude all air from the dielectric, but I do not think it is easy to exclude oxygen, which the impregnating compound picks up from the atmosphere in the process of manufacture, and this oxygen, becoming ozonized, may lead to breakdown.

Mr. A. Monkhouse (*communicated*): The author's theory seems to me to be far more probable than anything else that has yet been published, and the astonishing point about it is that it so successfully correlates and confirms in a very simple manner the work of previous investigators who have attacked various sides of the problems which arise in considering the behaviour of dielectrics when subjected to electrical stresses. The author makes no reference to the work of Mr. Takeo Akahira (*Journal of the Institute of Electrical Engineers of Japan*, August 1923), who published some exhaustive tests on the effect of temperature and humidity on dielectric losses in fibrous dielectrics. These tests also brought out very clearly a falling-off in the value of the dielectric loss when plotted against time if the test is continued for a sufficiently long period. I have frequently observed the same phenomenon when making the highest maintained a.c. stress test on fibrous dielectrics as laid down by the Electrical Research Association, but in this case it is a significant fact that the thermocouple reading also shows a corresponding drop in temperature. The explanation of this would seem to be that the increase of temperature due to the I^2R losses in the dielectric when the stress is applied, actually dries out the moisture and increases the value of R, thus resulting in a corresponding diminution of I and consequently of the dielectric loss and of temperature-rise. Incidentally, the highest maintained a.c. test of the E.R.A. has not been mentioned by the author, but I think that this test when properly carried out is capable of affording one of the best illustrations we can have of the behaviour of dielectrics under stress and during actual breakdown, and it is to be regretted that it has not been more widely adopted. It also affords an excellent confirmation of the pyro-electric theory of breakdown of fibrous dielectrics which, I am sorry to see, the author is inclined partially to condemn, because he considers it ignores the time/voltage relationship, the importance of which he very rightly emphasizes in Section (VIII) of the paper. As I understand the pyro-electric theory, it allows that the heating due to leakage currents through the dielectric reduces the value of R and thus increases I until the rate of heating is greater than the rate of heat dissipation of which the dielectric is capable, and then the effect becomes rapidly cumulative and quickly results in a temperature being reached which produces chemical and physical changes and subsequent breakdown. Since the rate of heating, and thus the time elapsing before critical conditions are reached, is dependent on the value of I, which, in turn, is dependent on the applied voltage, it seems to me that the author is wrong in stating that the theory ignores the time/voltage relationship; in fact, his I^2R theory helps to explain and confirm the pyro-electric theory. Moreover, it is apparent that once the above-mentioned chemical and physical changes have commenced, even if breakdown is prevented the dielectric has deteriorated. In Section (IX) the author ascribes the pyro-electric theory (as he names it) to Wagner and mentions that it was concurrently advanced by Hayden and Steinmetz, but I think that Prof. Miles Walker first advanced the theory in the discussion on Dr. Rayner's paper on "High-voltage Tests and Energy Losses in Insulating Materials."* I therefore suggest that it would have been more correct to have stated that the valuable work done by the well-known research workers named confirms the theory first put forward by Prof. Walker. Fig. 46, in which breakdown voltage is plotted against the inverse fourth root of time, is exceedingly interesting. The E.R.A. has, until now, taken the "minute value" as the basis for its standard tests for determining the electric strength of materials of various thicknesses and at various temperatures. Although in the past I have strongly advocated the "minute value," I am now not at all sure that the value shown as X, if it could be determined for insulating materials of various thicknesses and at the various temperatures advocated by the E.R.A., would not be of greater commercial value to designers, etc., than the "minute value" figure. It would be interesting to know how the values of X obtained as the author shows, compare with the figures obtained by the E.R.A. highest maintained a.c. stress test. Theoretically they should be approximately the same. In connection with Fig. 26 the author does not mention what are the fibres employed in the two papers A and B. The E.R.A. recently published the results of electric strength tests on papers made from various fibres. These tests showed remarkable differences in the properties of what had previously been regarded as reliable papers, when tested at temperatures in excess of 60° C. Manila, cotton, linen and jute all figure in the manufacture of electrical papers, but, as yet, few engineers appear to appreciate the great differences that exist in the behaviour of these fibres when employed at the maximum temperatures now permitted for Class A insulation. Even greater differences can be obtained by variations in the processes of preparing the fibres for paper manufacture. There seems to be need for closer co-operation between the

* *Journal I.E.E.*, 1912, vol. 49, p. 323.

botanist, the papermaker and the electrical engineer before the great potential possibilities of papers and pressboards as insulators (particularly for e.h.t. work) are fully appreciated.

Mr. P. Dunsheath (*in reply*): I agree with Mr. Fuller that we shall have to go to the atom for the explanation of absorption, and I am very interested to note that his experiments show the presence of the "V" curve, both in the dry paper and in the oil alone. In reply to the latter part of Mr. Fuller's comments, I should say that not even a gap of a few mils would be necessary to deflect the stress from a purely radial direction; a difference in contact pressure between papers might conceivably be sufficient.

Mr. Morland's suggestion of heating and cooling a cable through many cycles, combined with a power-factor test as a criterion of quality, is along the right lines. The power factor measured is, of course, only an average figure for the whole length and it is possible to change the power factor dangerously at one point by such a series of heat cycles without appreciably affecting the average power factor over the length. Entrapped air, as suggested, is, of course, the great enemy.

Mr. Robinson's account of experiments with aeration of oil, and Mr. Cave's observations on oxidation, are both very interesting. In the ordinary manufacture of impregnated paper cables, the oil is heated to temperatures higher than those employed in service. In this operation the oil is, of course, de-aerated and, as suspected by the speaker, this is an important point. On the question of allowable head of oil, it is impossible to lay down hard-and-fast rules as there are so many factors involved and each case must be considered on its merits. On the other hand it may be safely taken that, the more fluid the oil used, the more necessary does it become to design all parts mechanically to withstand internal pressure on both the sheath and the joint box and, what is equally important, to keep the cable filled from the upper end. Because of this difficulty there is much to be said for using viscous oils. In constructing the models referred to by Mr. Robinson, points were taken every 10 deg. C. of temperature and every 5 kV of pressure.

Mr. Bolton's short question would justify a long reply. The comparison of various cable papers is an interesting, though difficult, study—difficult because of the many variables which must be eliminated in order to arrive at true conclusions. Briefly, however, manila paper does not stand heat treatment so well as papers made of certain other fibres, and is more difficult to impregnate.

In reply to Mr. Collie's query, the loss that takes place in the dielectric of a network is, of course, a function of two quantities, the dielectric power factor and the charging kVA. For a system of a given electrostatic capacity, employing a cable of a given power factor, the loss is independent of the type of cable. It is, of course, less under d.c. than under a.c. conditions. As regards the selection of a suitable test pressure, the cable makers are in agreement on cables for working voltages up to 11 000, but standards have not yet been fixed for the higher voltages.

I very much appreciate Mr. Monkhouse's kind references to the paper and the valuable observations which he has communicated. The drying-out of moisture on paper samples, as noticed by the Japanese investigator and by Mr. Monkhouse himself, could not occur in a lead-covered cable. In such a cable the power factor, rather than falling with time, is inclined to rise. Again, there is not much published evidence at present of a highest maintained a.c. stress in cables as employed by the E.R.A. for dielectric samples. Mr. Farmer, of the New York Testing Laboratories, is working on this subject and has recently given some interesting results in a paper read before the American Institute of Electrical Engineers, but the nature of the time/voltage curve for very long times is, of course, difficult to determine. Mr. Monkhouse, after stating that he would like to see me more in favour of the pyro-electric theory, proceeds to enunciate a new pyro-electric theory in which chemical change is introduced. My objection to the theory, as already published, is that all time effects are due to heating, and, therefore, steady conditions should be attained within a few hours; whereas we know definitely that the time effect in cables may continue for months. If a chemical change is to be included in the pyro-electric theory, then my views will be different from those stated in the paper, but such a radical change constitutes a new theory. Prof. Miles Walker in the discussion on Dr. Rayner's paper in 1912 certainly analysed the heating conditions in a dielectric under stress, but he dealt rather with mass heating. I think the essential feature of what is to-day known as the pyro-electric theory is the cumulative heating of individual filaments to temperatures higher than those of adjoining parts of the same dielectric. Mr. Monkhouse confirms the view of many other investigators that the nature of the fibre of which the paper is made is all-important, and I agree with him that very careful selection of paper is necessary in order to obtain the best results in dielectrics to work at high temperatures.

DISCUSSION ON "JUSTIFIABLE SMALL POWER PLANTS."*

EAST MIDLAND SUB-CENTRE, AT LOUGHBOROUGH, 19 JANUARY, 1926.

Mr. W. Pearson: The paper shows how dependent is the overall cost of power upon factors other than those commonly regarded as decisive, and, while justifying very small power plants operating under special conditions, it indicates the necessity for judging on their own merits the straight condensing generating stations of medium capacity. It is obvious that the really large station is necessary for the supply of a large concentrated load; but, as a rule, a plant of medium size can supply current much more cheaply to the area within reach of the generated voltage than a much larger station supplying from a distance, and it is difficult to see how a local advantage of this character can involve any national disadvantage. The claims put forward on behalf of super-stations supplying wide areas are based on three assumed advantages:—(*a*) Higher efficiency, (*b*) lower capital cost, and (*c*) better diversity factor. The last-named is generally fallacious in this country owing to the very general standardization of working hours, and whilst an increase in the load may be accompanied by an improvement in load factor, there is no reason why this should be more pronounced in the case of the large plant than in the case of the comparatively small one. For example, St. Helens, with a plant capacity of 11 000 kW, has a load factor of 62·36 per cent, and Maidstone with a smaller plant capacity has a load factor of 41·8 per cent, as compared with Manchester's 31·99 per cent. These figures are sufficient to show that load factor does not depend on the capacity of the generating plant. It might be expected that the large stations would, by reason of higher efficiency, show a lower fuel cost. It is, however, interesting to note that the largest undertakings for which returns are accessible (Manchester, Glasgow and Birmingham), have *coal* costs of 0·25d., 0·23d. and 0·29d. per unit respectively, as compared with Rotherham, Walsall and St. Helens, 0·19d., 0·23d. and 0·25d., respectively. Two of the above are really small stations. If total *working* costs are taken into account the three large undertakings are 22nd, 35th and 43rd in the list respectively, and of the first 30 stations the majority have total capacities of less than 25 000 kW. If a comparison be made of the total cost, or say the *average price* obtained for the current produced, the figures for Manchester, Glasgow and Birmingham are 1·32d., 1·64d. and 1·44d. per unit respectively, as compared with St. Helens 0·83d., Stalybridge 0·89d., Rotherham 1·0d. Evidently other factors are at work besides those to which so much publicity has been given in recent years. As regards capital cost, it is not generally appreciated how much the civil engineering work connected with a super-station increases the cost per kW of plant installed. Recent installations indicate that, while a fully equipped station as small as (say) 15 000 kW total plant capacity can be built for less than £13 per kW, the cost of large stations works out at £18 to £20 per kW; and experience has shown that stations equipped with large plant require, if anything, a higher proportion of stand-by plant than small stations. A station with six sets installed would necessarily have two in reserve, and a load factor of 33⅓ per cent based on the maximum capacity of the running plant would therefore represent a load factor of only 22·2 per cent on the maximum capacity of the plant in the station. If the total capital charge be taken at 8 per cent an increase in cost of (say) £5 per kW of installed capacity would nullify, as regards total cost of current, a gain of 20 per cent to 25 per cent in the fuel cost. The exponents of the super-station idea have usually based their arguments on comparisons between a small station with obsolete plant and a large station equipped with modern plant. If the comparison is between modern plant in both cases the maximum advantage which can reasonably be claimed for the large station is 10 per cent, and the figures of actual performance in this country show that even this claim is not justified by experience. If therefore the large modern station is unable to charge a lower average price to the consumers in its own immediate neighbourhood than the modern medium-size station, how can it be expected to supply at a distance (involving heavy additional capital charges upon transmission lines and transformers as well as losses in the transformation and transmission) more cheaply than the medium-size station located near to its load? The super-station is still more handicapped in respect of capital charges if compared with the installation of modern plant in an existing generating station, as the charges on the outstanding capital must be met even if a bulk supply is obtained. It is surprising how generally adaptable stations designed for reciprocating plant are for modern turbine plant of 5 to 10 times the capacity. Such developments usually involve no additional capital charge for stand-by plant, the best of the old equipment being satisfactory for this purpose. One cannot help feeling that the propaganda of the past 7 years has given the public and the Government a very erroneous idea as to the advantages of centralized generation, and the author is to be congratulated upon having presented some of the facts on the other side.

Mr. A. G. Deverill: A study of the tables of costs published in the *Electrical Times* shows that super-stations are uneconomical, and I am in favour of allowing existing stations to be equipped with economical plant, to be linked up one to the other. I contend that the supply of electricity to the consumer would be cheaper by this method than by putting down large super-stations and carrying the current long distances.

* Paper by Mr. A. B. Mallinson (see vol. 63, p. 896).

One point in favour of the small stations linked up is that they would none of them require to have 100 per cent of spare plant, such as any station has to have at the present time, as their interlinked stations would be a perfect stand-by to one another. On this point it is significant to note that, even in the East Midlands scheme, such a station as Loughborough with 6 000 kW installed and selling at the present time 4 400 000 units per annum could very easily supply another 20 000 000 units into the linked-up lines if consumers could be found to take this amount, and moreover, as the capital charges all exist on the present number of units, the additional units would be sent out into the lines at a modest profit on just the running charges. In this way the small stations would be fully loaded and long-line distribution losses would be avoided. It is obvious also that in most industrial areas in Great Britain, coalfields are somewhere near, and, whereas the freight per ton of coal is usually about 8s. 6d., I think it would be much better to generate, wherever possible, by any small or moderate-sized station in proximity to the coal rather than by very much larger stations where the chief consideration is a plentiful supply of water for condensing purposes. The larger station usually costs more than the smaller station to build and equip, and a complete power station of 10 000 kW capacity in three units of 3 000 kW normal capacity could possibly be erected for £132 000, or £13 per kW, whereas a larger station built near a river or in close proximity to a large water supply would probably cost very much more in its civil engineering requirements. The smaller station could generate just as cheaply as a station of the size of Barton, where the units cost 0·73d. at the works, to which have to be added the full amounts for capital on plant and mains. It is obvious that the so-called super-station could not have the effect of bringing down the price of electricity. For instance, Manchester has to obtain an average price of 1·32d. per unit and, whereas it was stated that a far greater consumption *per capita* would have the effect of reducing the price, this could not be done unless a very large additional number of higher-priced units were demanded and sold than will probably be the case. The newspaper talk of 1d. per unit for electricity does not attract industry at all. A works of any size would have to get its power for, at any rate, not more than ½d. per unit, and, to sum up, I think that the smaller stations linked together will provide a far better solution than will a number of large stations.

Mr. E. G. Phillips: The engineer who tries to prevent the loss of British thermal units in a modern boiler house is to be commended, but it is difficult to understand why the same individual never attempts to deal with the 60 per cent of the total heat available that is constantly escaping into the circulating water. Is it not a fact that electrical engineers on the "generating side" are too scientific to be commercial, and that they think it *infra dig.* to consider the sale of so common a commodity as hot water or even exhaust steam? My experience is that in all industrial plants, where steam is required for the "process," it is never possible for the super-station to compete even on a coal-consumption basis, ignoring the high standing charges so inseparable from these stations and their distribution networks. I do not agree with the author that the steam demand will usually be found to coincide with the demand for power; the reverse is usually the case, but this need not affect the design of such equipments. In a brewery recently completed on the back-pressure system, a battery of 5 boilers proved insufficient to deal with the steam peaks, and the power was obtained from gas engines. The present results are that 3 boilers easily supply the whole steam and power, whilst frequently only two are required. Whilst the demand for steam exceeds the exhaust available, the process main (at 60 lb./sq. in.) is fed with make-up through a relay-operated steam valve on the high-pressure main. When the exhaust exceeds the amount of process steam required, the surplus is automatically by-passed to several large thermal storage tanks and stored as hot water against the next "brew," when it is pumped to the brew tower at a temperature approximating to the final temperature required. This arrangement allows the boilers to be steamed at their most efficient load all day, irrespective of demands, supplies boiling water to the process (thus preventing delays) and also obviates the original heavy peaks on the steam side. My experience has been that the 10 per cent allowed for as lost while passing through the engine is in excess of actual practice. One great difficulty is that the existing process steam mains are insufficient in area to pass the amount of steam required at a lower pressure, and that in consequence it is frequently desirable to carry a higher back pressure than is necessary, due to the excessive cost of re-piping the works. This is a matter of little importance where the amount of exhaust made available by the high back-pressure is not in excess of the requirements for process purposes. The surprising thing is that, whilst those who have had little or no technical training in engineering matters somewhat naturally display an almost unbelievable ignorance of the great advantages of the use of back-pressure prime movers, men of prominence in the Institution still refer to the advocates of small plants working on this high thermal efficiency as cranks, and thereby create an entirely false impression amongst those who believe all they read and rarely think for themselves. Why does the British technical Press hardly ever devote any space to educating engineers and other readers to the possibilities of running small plants at 60 per cent thermal efficiency instead of purchasing from a plant rarely attaining more than 18 per cent? The American journals have, in almost every issue, descriptions of plants so working and also articles dealing with this matter in one form or another. The British technical journals suffer from an apathy which cannot be understood by those who are constantly engaged in work of this character. Cannot this inertia be overcome?

Mr. A. B. Mallinson (*in reply*): Mr. Pearson and Mr. Deverill have both dealt with the justifiable small power station as a straight condensing plant. At the present time, when the Electricity Bill is much in evidence, these remarks are of interest and I am quite in agreement with the views expressed. Where buildings have been erected close to available water, and

distribution mains radiate from them, it would obviously be a sound policy to modernize such plants and work the stations up to the full capacity of the site, whether limited by condensing water, buildings, plant capacity, or distribution. No doubt the Commissioners consider each case very carefully on its merits, but the points raised by both Mr. Pearson and Mr. Deverill are well worthy of serious consideration in view of the way the public is being led to believe that the super-power station is going to be *the only way* to get cheap electricity. I would particularly emphasize that whilst in the last few years there have been considerable improvements in super-power station units of 10 000 to 40 000 kW, there have been even greater improvements in the operating efficiencies of units of 500–3 000 kW. The only way to make a fair comparison is to compare the super-station with the small, straight condensing station where the plants are each of the same age.

The case of a brewery cited by Mr. Phillips shows how easily one can maintain the efficiency of these combined plants, even when the cycles of power and heating demand do not coincide. In bleach and dye works I have used thermal storage in the same way by storing up hot water. I have also seen plants working on thermal storage with the Ruths accumulator as a balancer. Similarly, on the other side, particularly applicable for institution work, the balance of cycles can be obtained by a storage battery, which also enables the plant to shut down through the night shift. I agree with Mr. Phillips that 10 per cent for condensation is in excess of actual practice, but I took that figure to be on the safe side. Personally, my experience has been that 6 per cent is ample. The amount of pipework used with low-pressure plants is the secret of success or failure. Many plants have been condemned on this point alone. As Mr. Phillips remarks, it is difficult to understand why technical men in England are so antagonistic to the installation of small back-pressure or heat-extraction plants. One reason for discounting the economies of such heat and power dual plants among power supply engineers is apparently that the costs per unit of such plants are not generally available. I have recently seen the operating figures of 8 plants, the works cost varying from 0·152d. to 0·302d., average 0·212d. The general run of such plants are, however, installed without meters; what the owners are concerned with is not units of electricity but overall operating cost for power and process heating. The British technical Press is much to blame in this respect; it seems to look upon the small heat-extraction power plants as being unworthy of notice, yet there is seldom an issue of the American paper *Power* without reference to such a type of plant.

I am writing this reply at a time when the country is entirely dislocated by a general strike. One hears that some London hospitals have had all their supplies of electricity cut off. Is not this another very sound argument in favour of the installation of these small power plants in public institutions and the like, thus enabling those in charge to be in entire control of their own operations in times of stress and in normal times to run on the cheapest possible lines, for themselves, the ratepayers and the country as a whole, by the conservation of coal ?

DISCUSSION ON

"AN ALL-ELECTRIC HOUSE." *

NORTH-EASTERN CENTRE, AT NEWCASTLE, 8 FEBRUARY, 1926.

Mr. W. F. T. Pinkney: Even to those of us who are familiar with the various uses and applications of domestic electricity, there are many matters dealt with in the paper which suggest new possibilities. The author's house has been extraordinarily well laid out electrically, and there are details of refinement of application which are of great interest. My own house was equipped for lighting, heating, cooking and water heating some 12 years ago, and whilst my own installation lacks the detailed refinement of the author's, it is not without interest that the general applications of electricity are very similar, although there has been no alteration to the installation other than the introduction of more modern appliances during the period. The house is an old one, and not specially designed for electrical equipment. The Newcastle Electric Supply Co. has no tariff comparable with the No. 1 Glasgow tariff, and the unit rate of the company's two-part tariff is not as favourable as that in Glasgow. The Newcastle company's two-part tariff is, however, available in remote towns and villages where the competitive forms of lighting and heating are much more costly than in Glasgow. The author refers to the cost of his house being increased by from 3 to 4 per cent by his electrical installation, but it should be noted that many details, such as the multiple switching, could not be installed in any house other than an electric house, so that it is perhaps incorrect to compare the cost of this house with a house not electrically equipped. On the question of the cost of supply the two-rate meter for registering night consumption is itself a costly item, and if multiplied by thousands would represent a very large additional capital expenditure. The consumption of energy at my own house is higher than the author's for heating purposes. This is due, however, to a very lavish use, and to exceptional uses in connection with hobbies. The cooking consumption is under 1 500 units a year, taking an average of 10 years and an average household of 4½ persons. The author's consumption for cooking seems to be on the high side. My lighting consumption is the same as the author's, and the hot-water consumption very similar, that is, 6 550 units a year (average over 10 years). The hot water is controlled by a thermostat. The hot-water cylinder is polished but unlagged, and of 30 gallons' capacity. The piping is unlagged and the heater is a circulator and not an immersion heater. It is reasonable to suppose that the consumption for water heating would drop if the system were brought up to date. I have experienced no difficulty with refuse disposal, the arrangement being similar to the author's, except that there is an existing kitchen grate in which waste paper, etc., is burned each day. On the question of reliability of apparatus, the results vary enormously in different households. In many cases where electricity is used very extensively, such as my own, maintenance costs are very low. There has been no maintenance on the water-heating system in 12 years, and practically none on the cooker in 3 years. In the case of some of our consumers, however, maintenance costs are unduly high, which points to unfair use of the apparatus. It may interest the author to know that the Newcastle company supplies energy to 5 groups of houses specially designed and equipped for the use of electricity.

Mr. H. W. Clothier: When one considers that the author is using in his house, per person, 2 756 units per annum, which is perhaps 30 times the average for this country, it is easier to realize what is required of future power stations. Everyone knows the difficulty experienced in obtaining efficient domestics. The full development of electricity in the home, avoiding waste of labour, is the ideal for which to work. How much of the prosperity of the United States is due to the use of electricity and other labour-saving domestic devices, thus liberating the personnel for productive work and thereby contributing to the national wealth? A panel of the B.E.S.A. is about to issue a new Specification for a protected type of wall plug and socket with metal casing, efficient scraping earth contact and visible earth terminals. These plugs and sockets are rated for 5, 15 and 30 amperes, and the interchangeable dimensions could be applied for inlets for the kettle, flat iron, radiator, curlers, and every other kind of "portable apparatus." It has been said in the electrical Press that we should not encourage the use of the latter in the bathroom. What are the author's views on this question? Would it not be better to develop the earthing of all portable apparatus, with a reliable form of 3-core flexibles, than to condemn the use of electricity in any specific parts of the house? The sockets in the four-room flat are not provided with switches. I presume this is because it saves much expense, and that plugs, particularly of the protected type in which the arc is encased in earthed metal, will break circuit without danger. A plug used as a switch has the advantage of forming a simple double-pole breaking device and it provides a complete isolation. I believe that some economy in house wiring would be effected by a wider application of this system for switching, and that the I.E.E. Wiring Regulations need only slight modification to put it into effect.

Mr. P. Ward: The cost of the house is assumed to be 3 or 4 per cent more than would have been the case if it had been equipped with coal and gas apparatus; the number of heating points installed is greater than is necessary, and the multi-control on the lighting installation is also very elaborate. These items go a considerable way towards making up the extra 3 or 4

* Paper by Prof. S. P. Smith (see page 289).

per cent. I notice that there is no scullery, and I would suggest that, particularly on washing days, a scullery is desirable, otherwise the damp air from the kitchen will go all over the house. I should have put the distribution board in the cloak-room. Were alternative prices for wiring obtained? In a paper recently read before the Dundee Sub-Centre, figures were given showing the cost of rubber-covered installation as 90 per cent of the cost of a screwed conduit job. It therefore seems reasonable to assume that an installation in split conduit with grip fittings could be put in at a lower cost than the rubber-covered installation, with the result that the 3 or 4 per cent additional capital expenditure would be further reduced. Presumably the bell installation is also counted in the cost of equipment, but as there would be such an installation in the house in any event, this also appears to be an item contributing towards the extra 3 or 4 per cent. With regard to the drying closet, the loading appears to be very low. It is certainly very much lower than that of any built-up cupboard at present on the market. It would be interesting to know to what temperature the chamber is raised before clothes are put in, and how long it takes to reach that temperature. It is stated that a cupboard full of clothes can be dried in 1 hour, but I hardly think this can apply to heavy goods, sheets, etc. With regard to the cooker, I notice that a table type is in use, and this is preferable wherever sufficient floor space is available. Open-type hot-plates have been used, and I would ask whether the author has ever used any totally enclosed plates, and, if so, which he really prefers, and why. With regard to the efficiency of hot-plates, it is very misleading to state what efficiency is obtained unless the conditions are known. In some tests recently carried out on a number of hot-plates under two different sets of conditions the efficiencies were found to be as follows:—In the first set of conditions, average efficiency 20·2 per cent; in the second set, average efficiency 34·1. In these tests the plates were switched on from cold. Similar tests taken with the plates already hot gave average efficiencies of 31·4 and 49·8 per cent respectively. The highest individual efficiency obtained was 67 per cent. With regard to the suggestions that self-contained vessels should be used, these, of course, are far more efficient, but experience has shown that their maintenance is more costly. When using self-contained vessels of the plug-in type it is difficult to remove the vessels from the sockets without splashing over the liquids contained in the vessels. The pins must fit tightly into the sockets to make good electrical contact. Reliability and safety are more important than efficiency. In connection with the hot water supply, whilst I agree that the heat loss is much less at 140° F. than at 180° F., it is doubtful whether for all-round purposes the best results are being obtained. By using smaller hot service pipes and running the cylinder at a higher temperature the heat losses can be cut down, and water sufficiently hot for washing dishes can then be obtained at all times of the day. The water requirements also appear to be above the normal and I think that 25 gallons will be found sufficient for a normal bath. With regard to ventilation, sufficient outside air comes in from the door and window frames in most modern buildings. The author's ventilation scheme could not apply to semi-detached or terrace houses, as external chimney breasts could not be used. I think that the best and cheapest way of ventilating rooms is by leaving an opening over the doors into the hall and by providing a fan-light over the window; by this means the vitiated air can be removed from the upper part of the room and cold draughts across the floor are avoided. Under the author's scheme it is possible to get a draught from the ventilator behind the fire, across the floor to the door. It is agreed that, for domestic purposes, heating by radiation is preferable to heating by convection. The author gives a temperature of 50° to 55° as being suitable, but normal experience shows that 55° to 60° F. is more usual. It is certainly better to heat a room, particularly a large room, from several points rather than from one, but habit dictates that all should sit round one fire. The author's consumption for heating purposes appears to be rather low; this may be due to the fact that he finds a temperature of 50° to 55° F. sufficient for his purpose. His cooking consumption appears to be higher than is usually the case for a similar household. His lighting consumption is extremely high and it would be interesting to know what is the kilowatt capacity of his lighting installation, and whether small apparatus such as kettles and irons are used from his lighting system. If the author's lighting consumption were calculated at the ordinary lighting rate prevailing in the district and deducted from his total running costs, it would be seen that his heating and cooking costs, including hot-water supply, amount to only £32 15s. per year.

Miss A. Holm: It is interesting to note that a wash boiler only is installed for laundry-work purposes. Clothes must be washed and need not be boiled, therefore I think that an electric washer would be much more useful as it would provide the means of washing silk, woollen and coloured articles as well as white clothes. The self-contained cooking vessels must be excellent for rapid heating, and I can appreciate the advantages of these for large pans such as stock-pots, steamers, and French frying baths. For general use the disadvantage of weight, the awkwardness of manipulation and the difficulty of cleansing would be against the popular use of these. Saucepans are most easily cleaned by immersion in hot water. I would suggest that a small open element would be convenient and would afford rapid heating for small pans used for sauces, etc. No provision for drying and warming towels is shown in connection with the bathroom; these could be arranged near the tank, or an electrically heated towel rail could be used. Mr. Ward raised the question of the disposal of garbage in an all-electric house; he said that it becomes a problem if the collection is only made bi-weekly by the sanitary department. This need not be so if the housewife adopts the method used by the Canadian housewife who wraps the refuse—as dry as possible—in small parcels, using newspapers for this purpose. This prevents smell, flies and rapid decomposition, and disposes of the daily papers in a convenient way. The intelligent woman wants an all-electric house, because home management can then be carried out scientifically, and leisure hours result. That it should

be the means of dispensing with the domestic servant is possibly an advantage, but many may still require this service, and the work in the electric house should appeal to a better and more intelligent type of domestic servant, because of the lack of drudgery in the daily work which is associated with the ordinary household without electrical conveniences.

Mr. R. W. Gregory: At the discussion on this paper in London, to my mind the most serious criticism was that by Dr. Margaret Fishenden, in which she pointed out that the energy consumed in the author's house for warming was only equal to that of one coal fire, and she feared the cold walls. The English are notoriously weak in the science of house-warming. They have the coldest houses in the civilized world—and are inclined to glory in the fact. I feel, however, that it only needs a few seasons of super sun-spots to raise the standard of heating required by the ordinary English householder. He will expect his home to be at least as comfortably warmed as his office or his factory, and he will think the cold passages and spot-heated rooms of the present-day barbaric. When this demand for really warm houses arrives, shall we be able to supply the necessary quantity of heat electrically? In my own house I have a central heating plant, burning coke, which keeps the house generally at from 50° to 55° F. In the living rooms I "top up" with a small coal fire. If I could obtain electricity cheaply enough, I should use it for topping-up purposes, but heat at 3d. per unit is beyond my purse. Could I use electricity for the central heating plant? These are the figures:—Average fuel consumption 5 cwts. per week. Cost of fuel 10s. per week. B.Th.U. in fuel consumed—$560 \times 12\,000 = 6\,720\,000$. B.Th.U. obtained for warming (boiler efficiency 60 per cent) = 4 032 000. An electric boiler with an efficiency of 95 per cent would consume 4 240 000 B.Th.U. or 1 230 kWh per week. With electric heating, fine control can be obtained, and this control can be automatic. This would eliminate much waste of energy, for with my coke boilers fine control and efficient stoking are difficult to obtain. I think, therefore, that one could assume that 800 units per week would give a satisfactory supply of heat to the house. To obtain this electricity at a cost equal to that of coke to do the same duty, the price per unit would have to be 0·15d. If the price were 0·3d. per unit it might still be worth while, for the sake of cleanliness and saving of labour, to use electricity in this way for house-warming. To obtain electricity at anything like this price it must be used at off-peak hours—and thermal storage would be necessary. This of course is already done in large buildings on the Continent, and a plant suitable for dwelling-houses might easily be developed. It is interesting to note that if a gas boiler were used instead of an electric boiler for this central heating system, assuming equally facile control, a boiler at 80 per cent efficiency, and gas with a calorific value of 475 B.Th.U. per cubic foot, 7 200 cub. ft. would be consumed per week. The equivalents therefore on my estimates in my own house for a central heating plant are:—10 cwts. of coke, 800 kWh of electricity, or 7 200 cub. ft. of gas per week. It will be interesting to see if electricity supply undertakings will ever obtain domestic loads such as this. As off-peak loads they are invaluable and worth trying for.

Mr. W. Cross (*communicated*): The electrical installation described in the paper is far more elaborate, as regards the switching and number of sockets, than the average consumer will install, and unfortunately the contractor preparing a scheme has to consider the initial cost if he wishes to obtain the work, though he naturally tries to influence the consumer to have a thoroughly up-to-date installation as described by the author. I am pleased to notice that the Wiring Regulations of the Institution were adhered to, as the cost of so doing does not appreciably affect the total cost of the work. The kitchen appears to be small, as it has to be used as a scullery and wash-house as well as a kitchen proper, and I should expect the vapour when washing to be rather objectionable. I am surprised that the author under-runs his lamps, as their life, if run at the correct pressure, is long. His efficiency is very considerably lower; if the pressure is 90 per cent of the normal, the watt consumption will be about 85 per cent of the normal but the lumen output will be reduced to 67 per cent of the normal. I am very interested in the suggestion that cooking utensils with self-contained electric heating elements should be used, as I can remember that about 30 years ago, self-contained saucepans, frying-pans, etc., were made in considerable quantities, though ovens and hot-plates were not then in use; possibly they will again be fashionable, especially as I understand they appreciably reduce the consumption of current for cooking. The tables giving the consumption and cost of current are of great interest, and show the importance of the heating and hot-water load to the supply undertakings, as well as the desirability of reducing the cost of current for these services if consumers are to use them to any extent. They also show that, with the tariff mentioned, one need not be specially careful in the use of current for lighting and, to a lesser extent, for cooking. In Table 3 the standing charge has been allocated to all sections, though it is an advantage from some points of view to allocate the bulk of the standing charge to lighting which is considered a necessity, thus enabling one to reduce the cost of current for other purposes which the consumer considers a luxury if it costs more than other methods.

Mr. F. H. Williams (*communicated*): Many of us, who never contemplated it a few years ago, have, since the war, been forced to become our own landlords, but usually the house so acquired has been far from ideal and the benefits which could be obtained from the introduction of electricity have been very much limited by this fact. My own house is a case in point and is a so-called 9-roomed house built some 20 odd years ago. To take advantage of the Newcastle-upon-Tyne Electric Supply Co.'s domestic tariff (the only tariff of the kind in existence in Newcastle at the time), the house was wired for electric light throughout, 8 heating plugs were installed in the principal rooms and electric cooking was arranged for. Under the domestic tariff in question there is a standing charge of 6s. 9d. per lampholder per annum, and all units, whether for light or power, are supplied at $1\frac{1}{8}$d. There are of course certain restrictions as to the minimum number of lampholders, and a certain

kilowattage of heating apparatus has to be installed. The rooms being fairly large it was appreciated that electric heating was out of the question from a financial point of view, and the power plugs were only put in for "topping up" purposes and vacuum cleaner, etc. It was also appreciated that an electrically heated clothes boiler was hardly attractive financially, either in first cost or in running cost, and, gas having been laid on, it was left connected to a wash boiler and a gas ring. The heating of the house and the hot-water supply is carried out by a combination of soft coal, anthracite and coke. The electric supply is 3-wire 250-volts (d.c.).

TABLE F.

Item	1923–24			1924–25			1925–26		
	£	s.	d.	£	s.	d.	£	s.	d.
Electricity * ..	17	13	9	20	8	0	18	1	5†
Gas	3	14	0	3	0	0	2	16	1†
Coal .. .. / Coke .. .. / Anthracite ..	23	17	6	22	10	6	20	4	0†
Total cost ..	£45	5	3	£45	18	6	£41	1	6

* Includes £2 12s. hire maintenance.
† Includes an estimated figure for the last quarter.

The cooker is on a separate circuit with its own meter, and the lighting and all power plugs are on another circuit. Table F gives the total cost of the various items for the past two years and an estimate for the current year. The family consists of 6 persons and it will be seen, therefore, that the costs are practically the same for similar conditions as in the author's house, but of course there are all the disadvantages attendant on burning the various fuels mentioned. The standing charge is approximately £6 per annum, and the actual units used were as shown in Table G. It will be seen that the units used in cooking are much lower than those given by the author, even if a percentage be added to compensate for the reduction due to the gas ring. Arising out of the general aspect of the all-electric house, I should like to ask the author if he has experienced any difficulty with domestic help due to the kitchen being fireless. The combined kitchen, scullery and wash-house arrangement described seems to leave a good deal to be desired from the point of view of the maid's comfort. In this part of the country where domestics are recruited mainly from the mining portion of the community, a good coal fire in the kitchen seems to be a *sine qua non*, and some of my friends have experienced difficulty due to the introduction of slow-combustion stoves in their kitchens. The author apparently approves of sunk-pattern switches. Whilst these are much neater in appearance than the ordinary pattern, they are more difficult to locate in the dark and the walls suffer in consequence. I have found it necessary to place a piece of celluloid beneath the switch covers to protect light wallpapers.

TABLE G.

Circuit	1923–24	1924–25	1925–26
Cooker	1 249	1 865	1 365†
Lighting *	778	757	876†

* Includes lighting, iron, vacuum cleaner, kettle and occasional use of two radiators.
† Includes an estimated figure for last quarter.

[The author's reply to this discussion will be found on page 790.]

SCOTTISH CENTRE, AT GLASGOW, 9 FEBRUARY, 1926.

Mr. R. B. Mitchell: I propose to deal with the subject only as it affects the supply engineer. The chief feature of the paper to my mind is the storage tank, and I have to endorse all that the author says with respect to the necessity for filling up all these valleys and V-shaped depressions in the load curves, and if these means are used generally it will have the effect in time of reducing the price of electricity. With regard to the rate of charge for night-time use, I must point out that this rate of ⅜d. is only applicable to heat storage; it does not apply to any other use of electricity at the present time. In the London discussion on this paper one speaker said that he had no doubt that a very considerable loss to the undertaking would be made in selling electricity at this rate, even during the night, and another said that he had no doubt that a handsome profit is being made. The real truth of the matter is that it is something between the two. There really is a profit so far as Glasgow is concerned in selling electricity during the night at ⅜d. For the past 7 months the total works costs at Dalmarnock average out at 0·228d. Last month the figure was 0·196d., and the month before it was even lower. There is thus some difference between the works cost, which after all is the only figure which comes into the calculation, because capital charges are not affected, and the selling price in this instance. One of the arguments which I think may be used against a supply of this description, i.e. a liberal use of electricity, particularly for heating water, is that, after all, the generation of electricity is very inefficient as the thermal efficiency of the very best of our power stations is only about 20 per cent. That may be so, but it will not always be the case, and various processes are being experimented with just now which will in time put electricity undertakings on a par with gas undertakings, as they will be able to use processes which will enable by-products to be taken from the coal before the residue is put under the power station boilers. If the supply undertaking can afford to sell electricity at a price at which the ordinary consumer can afford to

purchase it and be satisfied with the results, so far as the all-in cost is concerned, then it seems to me that that is all that matters.

Mr. A. P. Robertson: Mr. Marshall has asked me to say that in his opinion the author has made one very serious omission in the equipment of his house; he has not provided a sun bath. Various institutions have installed these appliances and I understand that the treatment has proved very beneficial. Mr. Marshall agrees with the author on the question of self-contained units for cooking. I understand that he has conducted experiments with these appliances, and I believe that efficiency is greatly increased by their use. This is borne out by the author's figures. The author has been very extravagant with heating points. Four heating points in one room is very liberal, and a smaller number would be sufficient for ordinary purposes and would reduce the cost. I do not altogether agree with running separate circuits from the central point for all purposes. It is a very expensive method. When lighting, heating and cooking are all charged at one rate, there is no necessity to be economical with lighting. If a light happens to be left burning all night, it costs less than ½d. Some figures of weekly consumption are given in Fig. B. This gives the weekly readings in kWh for one year from January to January. The middle period which is blank is the holiday period. During the first half of the year the house was run with electric cooking only and occasional electric heating, and coal fires. The next half was run with electric heating, cooking and lighting, and one coal fire in the kitchen only for the hot-water supply. In the first part a very high peak will be noticed. That should not be taken into account: it was due to illness in the house, when a radiator was kept on day and night. This cost 10s. 6d. per week, but the constant temperature could not have been obtained with a coal fire, and there was no disturbance to the patient due to dust and attention to the fire. The cooking load also goes up, due to there being an extra person in the house who was a little extravagant with cooking and inexperienced. In addition, invalids require much short-time cooking, which is certainly a little extravagant. It will be noticed that the second half of the heating line reaches a peak just before the New Year. This is due to the frosty weather, and my figures bear out that the heating this year has been more than last year. The two halves of the curve show the difference between a house with occasional heating and one with electric heating. There is little difference between the cost of the first two halves, including coal. During the first half there was practically no heating.

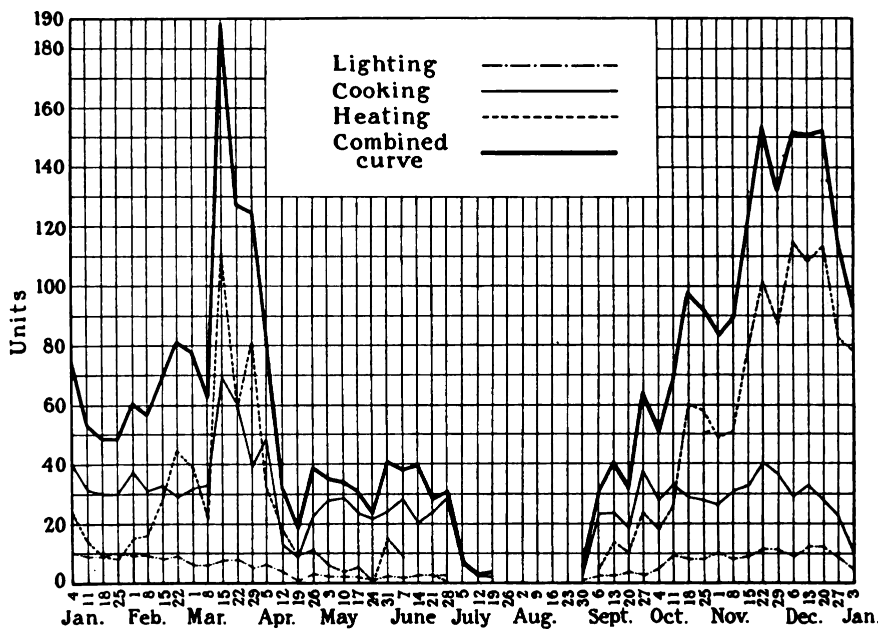

FIG. B.—Annual load curve for 6-apartment house.

The total cost of coal and electricity in the winter quarter of 1924 was £6 4s. 6d., while for the corresponding quarter of 1925 it was £5 11s. 4d. These are actual figures which I have taken from accounts. I only quote them to disprove the idea that it is very much dearer to heat electrically than with coal. The total costs are shown in Table H on page 782. I tried a good many different kinds of fires and I came to the conclusion that the fire that gives radiant heat is the best type. With the convector type it was found necessary to raise the total temperature of the room much higher than with the radiant type, which again bears out the author's contention that the atmosphere can be cooler if there is plenty of radiation. That of course if a great advantage, because cool air is better for the lungs. With regard to ventilation, my house was not built as an all-electric house and fireplaces were built in as usual. My wife at first refused any fire but a coal fire, but now we have no coal fires at

all. Ventilation is not difficult. I found that when the radiator was placed in the ordinary fireplace a great deal of the heat went up the chimney, and twice as much energy was used as was necessary. By partly blocking up the chimney, the room can be comfortably heated with half the amount of energy formerly used.

TABLE H.

Total Cost for the Year.

Electricity for lighting, cooking and occasional heating, with coal fires.

	£	s.	d.
Lighting—214 units at ¾d.	0	13	4½
Cooking—1 473 units at ¾d.	4	12	0¾
Heating—1 137 units at ¾d.	3	11	0¾
Coal—107 cwts. at 2s. per cwt.	10	14	0
Electricity supply standing charge	6	10	0
	£26	0	6

Electricity for lighting, cooking and heating, with coal fire for hot water only.

	£	s.	d.
Lighting—276 units at ¾d.	0	17	3
Cooking—1 316 units at ¾d.	4	2	3
Heating—2 994 units at ¾d.	9	7	1½
Coal—60 cwts. at 2s. a cwt.	6	0	0
Electricity supply standing charge	6	10	0
	£26	16	7½

There is plenty of ventilation in an ordinary house. Air comes in under the doors and windows, and windows can be opened slightly at the top if more air is wanted. The draught up the chimney is one of the most fruitful sources of loss of heat. In conclusion I should like to say that I agree with all the figures which the author gives.

Mr. R. Hardie: For the past 3 years my house, consisting of living-room, sitting-room, three bedrooms, kitchenette and bathroom, has been run on strictly all-electric lines. Electricity is charged on the two-part rate, i.e. fixed charge of £5 4s. per annum plus ½d. per unit for all current registered. There are four persons in the house. The annual bills have varied from £18 to £22, and I am satisfied, not only from my own previous experience but also by carefully comparing notes with tenants of similar-sized houses, that these figures could not have been improved upon had coal for heating and gas for cooking been employed. In addition, it must be remembered that the service was used without stint, and with an electric fire in every room a higher degree of comfort (particularly in the bedrooms) was obtainable than would have been the case had we been dependent on coal fires. There is, in addition, the saving in labour and avoidance of disturbance, due to the fact that no redecoration has been necessary over the 3 years, nor is the need for this even now apparent. A vacuum cleaner is in constant use, and an electrically operated clothes-washing machine, in addition to the usual numerous current-consuming devices. Details of the latest complete year are given below. The consumption for the year was 8 118 kWh (say 8 000), which, at ½d. per unit, comes to £16 13s. 4d. The annual charge was £5 4s., making the total £21 17s. 4d. The average cost per unit was therefore 0·656d.

The consumption was made up as follows :—

	kWh
Cooker and kettle	2 400
Water-heating	1 400
Living-room heating	2 500
Bedroom heating	1 300
Lighting and vacuum cleaner operated from lighting plugs	400
	8 000

Check meters were connected to the various circuits, and no coal was consumed during this period.

[The author's reply to this discussion will be found on page 790.]

SCOTTISH CENTRE, AT EDINBURGH, 9 MARCH, 1926.

Prof. F. G. Baily: The paper shows that such a house is practicable and, with certain precautions, not excessively expensive. The author's expenses are in fact little more than those of a similar house run on normal lines; but I know from personal trial how easy it is to economize in the consumption of electricity, though the ordinary person will pay half as much again for apparently the same services. Taking the chief items, cooking, warming of rooms and supply of hot water, while the first is normal for a moderate style of living, neither the warming of the rooms nor the amount of hot water would satisfy the average person who is used to comfort and has no special reason for economy. It corresponds more to the mode of life in a small flat, where saving of labour and avoidance of coals and ashes more than counterbalance the limitations, and the surrounding flats above, below and on both sides reduce heat losses in the rooms. For ordinary houses it seems a mistake to adopt electricity completely, when for some purposes gas, coke or coal are definitely cheaper or more effective or agreeable. In cooking, the electric oven is superior to either the gas or the coal-fired oven; but the electric boiling-plate has no advantages over the gas ring and is much more expensive. As the greater part of cooking is boiling, stewing and frying, the hot plate constitutes the larger part of the cost. I take Edinburgh prices for gas and electricity in the following calculations, viz. 8½d. per therm and ¾d. per unit. The electric hot-plate has a very low efficiency, given by the author as 25 per cent, and while this can be bettered I think that 30 per cent overall is the highest that can be given to it. According to tests I have recently made, the ordinary gas ring with a flat-bottomed kettle has an efficiency of between 50 and 55 per cent and with a kettle of improved design the efficiency rises to over 65 per cent, so that roughly the efficiency is twice as good. Since, total heat for total heat at above prices, electricity costs 2½ times as much as gas, the electric

hot-plate will cost 5 times as much as the gas ring for its consumption, and equally in first cost and upkeep the hot-plate is much the more expensive. The kettle with self-contained heating element has an efficiency of about 80 per cent, and with reasonable care lasts a long time, so its use may be considered, though its cost of running is still nearly twice as much as with gas, and it is more suitable for sitting-room use. As a practical point, the gas ring will boil a kettle in about half the time that the other two methods require, the hot-plate being the slowest. Self-contained cooking pots, which the author appears to desire, have been tried any time in the past 30 years or more, and the hot-plate has been introduced in their stead. They are expensive to purchase, heavy to handle, and the drastic washing that such appliances require soon destroys terminals, insulation and heating elements. Room-heating is a more complex matter. Coal fires have advantages which ensure their use in continually occupied sitting-rooms, and, while much is made of the smoke nuisance, it is a fact that the modern grate produces very little smoke, as can easily be observed in any suburb where the houses are not more than 20 years old. Between gas and electric fires there is little difference in cost. I made experiments on a small sitting-room in my house in which either gas or electric fires could be used, the sizes being selected so that each cost 1d. per hour, the gas being controlled to that consumption. The gas fire had a vent and the electric fire was placed alongside, but so that the hot air did not pass into the vent. The room was not occupied, entrance being made once an hour for reading the thermometers and adjusting the gas. This was favourable to the electric fire, as the loss of warm air was less than in ordinary use. Windows were shut and days were chosen when there was little wind, and the outside temperatures and initial inside temperatures were the same for the two tests. Repeat tests gave consistent results. Electric heating gave a more rapid effect, owing to the considerable warming of the air directly, while the gas fire operated solely by radiant heat to the walls and furniture. After some 8 hours the gas fire caught up the other, and after another 8 hours of cooling down the room was still slightly warm, while after electric heating it was quite cold. The gas fire puts more heat into the room at the same cost, but for short periods of use its effect is too slow. It was noticed that with the electric fire the room smelt stuffy, owing to the scorching of the air by the red-hot spirals, while with the gas fire the room was quite fresh, the comparison in both cases being with the air of a large sitting-room with an open coal fire. I consider that although electric fires are the best for occasional use for short periods, they are unsuitable for bedrooms when used as sick rooms, and the latter are better served by gas fires. Electric water-heating seems a vain idea for anything but a very small house or a flat. The coke-fired slow-combustion boiler is highly efficient, and, heat for heat, the price is so much less than for electric heating that a lavish use of hot water will cost considerably less than an exiguous one from electricity. Since for houses of any size central heating is the only effective method of general warming (preferably combined with small open fires in sitting-rooms) the hot water may be obtained by secondary heating from the same boiler, though there is an opening for electric or gas heating of water in the summer. It will be noticed that in the author's house there are no hot-water pipes allowing of circulation. They are all single pipes below the level of the tank, and all except one are close to the hot tank, so that only a short length of pipe needs to be emptied of its cold water. This arrangement very much diminishes losses by cooling, but restricts the positions of the hot-water supply in a way which would not be convenient in many houses. This particular house was designed for the purpose of electric operation, and is run with that object prominently in the minds of the occupiers; but if other considerations are allowed their natural claims the expense will be greatly increased. Finally, it should be remembered that there is no general warming of the house, such as is unobtrusively but effectively given by the flues of kitchen and sitting-room fires warming the walls through which the vents pass. This materially aids the drying of the house, keeping the air inside a little warmer than that outside, and in a self-contained house this is a matter of no small importance. Without it a house in this climate during the winter is certain to be more or less damp.

Mr. E. Seddon: I doubt very much whether the average user of electricity would consider the refinements made in wiring the author's house worth the extra cost, but one can readily see an earnest desire on the part of the author to show the amount of comfort which can be obtained with multiple switching points and extra heating plugs. His experience with water heating is most interesting and the remarkable efficiency of the lagging which he has adopted proves that hot-water storage is a practical and economical proposition. The immersion heater of, say, 3 kW fitted to the ordinary hot-water tank has great possibilities. One could rely on getting hot water in a definite time, whereas the boiler behind the kitchen fire is sometimes very uncertain. With regard to special low tariffs for night load, it is quite easy to see that any charge above the cost of coal will not result in a loss to the undertaking so long as the contour of the load curve remains where it is during the night, but if this part of the curve should cease to remain a valley the extra wear and tear of plant and other charges would operate against such low rates. In considering cheap tariffs for night load I am somewhat concerned about the law in respect of preferential treatment. As the law stands at present it seems to me that any consumer offering similar conditions of load whether, for instance, for ice-making or power purposes, is entitled to a rate similar to that offered for water-heating, and I think a great deal of discontent might result if an undertaking offering very low rates for this form of load is not prepared to offer the same rates for general purposes so long as the conditions of load remain the same. Looking at the author's account for electricity, I consider that his total bill would have been quite reasonable if he had not obtained the benefit of the $\frac{1}{8}$d. reduction during the night period. I might here mention that although we in Edinburgh have a comparatively large residential load as compared with our total output, the average price per unit sold

is within 0·02d. of the average price obtained in Glasgow.

Mr. W. Duncan : The paper is one of great interest to everybody connected with the electricity supply industry, as well as to contractors and to consumers. The supply undertaking's interest lies in the fact that here is a consumer who increases his annual consumption by some 16 000 units, when he starts to use electricity for all domestic purposes. To the contractor and also to the consumer the convenience and desirability of having a large number of plugs and control points is brought home in a very striking manner. It is the experience of most of us that the cost of wiring has to be considered very carefully. Convenience has to be sacrificed to economy, but it is false economy to have a very small number of plug points. Regarding the wiring of the author's house, I do not like the method of using lamp standards from a plug fused to carry 15 amperes, nor do I like the two-way switch arrangement in the bedroom. This fixes the position of the bed in the room for all time. This may have been satisfactory in the olden days, but in the modern electric house where there are no fireplaces the position of the bed can be altered at any time. A better arrangement is to have a portable lamp standard on the table at the bedside connected to a plug. The size or position of the bed can be altered at any time and the furniture re-arranged as desired. With regard to the arrangement for clothes-washing, I think that the author should have installed a modern electric clothes-washing machine instead of a wash-boiler. Hot water can be drawn from the main storage tank, and it is the experience of most users that the clothes washed in the machine do not require to be boiled. The water-heating arrangements are very satisfactory, and in offering such a low rate as 0·375d. per unit for a restricted hours' supply I think that Mr. Mitchell is to be congratulated. The switchboard diagram indicates that this rate applies for electricity for all purposes after 11 p.m., and not only for water-heating. The amount paid by the author for water-heating electrically compares well with the figure in my own case. I use a small coal-fired boiler, the annual cost of which is £5. The house is only half the size, and there are only half the number of persons in it to be catered for. Like Mr. Seddon, I was interested in the low radiation losses from the author's tank. The lowest figure that we have been able to find is 2·5 deg. F. per hour. It is a commonplace to say that the cost of an article is measured by the service rendered. In considering the cost of electricity it must be remembered that by no other medium can the same service be given. The standard of comfort, convenience and cleanliness is higher, whilst the amount of domestic drudgery which can be eliminated by means of electrically driven labour-saving devices is an item which cannot be assessed in terms of money.

Mr. F. W. Sharpley : I should like to submit the following facts and figures for the purposes of comparison. The figures refer to my own house or flat of five rooms exclusive of bathroom and hall, with three persons in the house, including a maid. Coal, anthracite, gas and electricity are used. The cost of the service for the year ending 31 January, 1926, was :—

	£	s.	d.
Coal and anthracite (partly estimated) ..	7	8	6
Electricity, power and lighting (2 meters) ..	4	4	3
Gas (for cooking)	3	10	0
	£15	2	9

The total cost per day per person works out at 3·32d. The total amount of electricity used was 636 units and includes the use of one 1½-kW fire, iron, vacuum cleaner, griller and toaster, in addition to lighting. For the purposes of comparison, I have estimated that if this house were in Glasgow, taking the same current consumption and demand, the cost would be £5 14s. on the two-part tariff, or £4 6s. 8d. on the ordinary rate, taking M (the number of units chargeable at 4½d. per unit) to be 150. That compares with the sum of £4 4s. 3d. already given for electricity actually taken in Edinburgh. Alternatively, I have estimated the cost of electricity for the author's house if this were situated in Edinburgh :—

	£	s.	d.
Lighting—568 units at 3¾d.	8	17	6
Power—100 units at 1d.	0	8	4
Remaining 15 916 units at ¾d.	49	14	9
Total cost (if in Edinburgh)	£59	0	7
Actual cost in Glasgow	43	8	0
Difference	15	12	7
Reduction if hot-water load on night rate, at 0·375d. per unit	9	8	10
Remaining difference	£6	3	9

If we estimate that in Edinburgh we could get energy for heating water during the night at the special restricted rate existing in Glasgow, then the difference is £6 3s. 9d. as shown above. The author does not mention the capital cost of the installation. I certainly consider that, at any rate, the difference between the cost of his all-electric house and what a similar house would have cost if equipped in the ordinary way for coal and gas with electric lighting, should be taken into account in the price that he pays per unit. In any comparative figures I think the number of servants in the house should be given, as it seems to me that even a single servant will make an enormous difference in the cost of running a house. The average servant has no idea of economy. I took the figures for our own house for the previous year, and I found that the cost of the gas and electricity services together were increased during the last year by 30·3 per cent over that for the previous year. In the previous year we had no maid, but this last year we had one. For hot-water heating I have an anthracite stove, and I find that it costs me almost exactly 2s. 6d. per week to give us an abundant supply of hot water day and night for all domestic purposes, and it gives us two good hot baths per day. That compares with the author's figure of 5s. 2d. per week which he gives in Table 3. We have a Ewart's gas circulator attached in case of emergency, but this is used in summer only, and then very occasionally. I should be glad if the author would give some particulars

of the lagging of his tank. He makes no reference whatever to the fireless cooker, and to my mind the fireless cooker seems the most economical way of roasting, baking and stewing. It will not poach an egg or fry bacon, but it does roasting, baking and stewing wonderfully well. It will cook meat, fowl, cakes, pies and puddings. I have one, and we find that if we heat up the iron discs which are supplied, on a gas ring for a matter of 12 to 15 minutes, we can put in a 3- or 3½-lb. joint and leave it in the cooker for the ordinary time, and be sure of finding it well cooked and ready. I believe that if these fireless cookers were fitted with a very low-rated electric element to prevent the cooling of food if attendance cannot be given for a long time, they would be ideal things.

Mr. A. Mears : The paper indicates the enormous field which is opened up for the use of electricity, and the possibility of improving the load factor of the stations. After all, costs can only come down provided load factor goes up. If load factor can be improved, the percentage of units lost in distribution will be materially reduced. This was brought out very clearly in Mr. Sayers's recent paper on tariffs.* With regard to the rate of ½d. per unit plus standing charge, this presents no great difficulty with modern plant. It is a method of charge which has a great advantage for lighting, and it does allow a user very great latitude with the use of lighting. Another feature which should be borne in mind is the labour-saving which electricity brings. We must put some value upon comfort. With a large house it is possible to save, because domestic service can be largely dispensed with. In the case of the smaller house the saving is not so apparent, but perhaps in time the housewife will realize that leisure and relief from uncongenial tasks have a definite cash value.

Mr. D. Martin : The question of cheap electricity is ever with us. Rates of ½d. and ⅜d. and even ¼d. per unit for suitable night loads are now available. A well-known electrical engineer member of Parliament has predicted a flat rate of ¼d. for all purposes in the near future, but I have my doubts about such a cheap flat rate when the cost of coal alone at present amounts to something like 0·15d. per unit in the best of the super-stations. The load curve at Glasgow (Fig. 5), however, shows how important it is we should find additional night load. The peaks at 11 a.m. and 4.30 p.m. are approximately 40 times that of the average night load, whilst the output as a whole is a daylight load. There is apparently no better method at present than that suggested by the author, viz. the accumulation of hot water during the night for the next day's domestic requirements. From a scientific and economic point of view, the production of hot water by electricity is unsound as a process by itself, but when combined with the scheme of things, as they exist, it is quite sound. There is a limit, of course, and the night load peak would not need to exceed that of the day load. To install new plant for an excess night load would not pay at the suggested tariff, which is the attraction at present. In general, any scheme which tends to flatten out the abnormal peaks is all to the good. In this respect the Glasgow supply system at present suffers somewhat by having no traction load from its tramway system; likewise there are no electrified railways in the neighbourhood, although there are fully half a dozen ripe for electrification. The practical effect of such a traction load would be to flatten the curve, due to the fact that the rush-hour loads come on before and after the peaks caused by the industrial loads. One obvious benefit with the greater output in units, with the same standing charges, would be a reduction in the standing charge costs per unit. I think that is fairly obvious. With regard to the costs of the author's installation, he has shown how the job should be done, but he omits to mention one important item of enormous advantage to the housewife. All his hanging fittings are suspended from the ceiling by means of plug adaptors. To release the fittings for spring-cleaning purposes and the like, all that is necessary is to unscrew a coupling at the ceiling. The need for a tradesman is thus eliminated. Again, he could have cut his wiring costs down by fully 80 per cent had he not run separate 15-ampere circuits from the fuse-board to each of the 31 plug points. Likewise, his multi-way switching points use up a great deal of wire. The extra convenience obtained, however, far outweighs the extra cost involved. A slight calculation will show how much more it would have cost if conduit had been used. For example, compare the costs of a 7-yard run of both systems. For vulcanized rubber cable in *screwed* conduit, customary and for long compulsory in Glasgow, there would be :—

	s.	d.
20 ft. of ⅝-in. conduit	2	11
1 bend	0	3·4
2 boxes for switch and ceiling rose	2	1
15 yards 3/·029 single-core vulcanized-rubber cable at 2·9d. per yard	3	7·5
Total	8	10·9

For C.T.S. cable clipped to pass the Institution Wiring Rules (Eighth Edition) :—

	s.	d.
7 yards 3/·029 twin-core C.T.S. cable at 10·9d. per yard	6	4·3
2 wood blocks for switch and ceiling rose ..	0	5
Total	6	9·3

This shows a saving in favour of C.T.S. of 2s. 1·6d. for a 7-yard run, equal to 3·5d. per yard for material alone. Labour is deliberately left out, but, if included, the saving would be still greater, as C.T.S. can be installed in half the time needed for conduit. In my own house where C.T.S. was used the total cost is a little under half the cost of the house next door where conduit was used. I have eleven 15-ampere plug points against my neighbour's 6, but otherwise the same lighting arrangements are observed, and fittings of similar price were installed. Here we have a big incentive to contractors to increase business, and another opening for supply undertakings to increase the domestic load. It is just this saving offered by an alternative wiring system which will make many a waverer decide in favour of

* *Journal I.E.E.*, 1925, vol. 63, p. 850.

electricity with all the advantages it has to offer. I know that the author has visions of the more universal use of electricity. Public opinion, with its increased knowledge of things electrical, is beginning to force the pace, and a far-seeing public servant should anticipate the public demand. The dreadful smoke pall which hangs over Glasgow and other cities in Great Britain is a disgrace to civilization. It once indicated great industry, but, with our present-day knowledge, it is acknowledged to be a sinful waste of our great natural resources, and it is for all of us to do our best to restore the clear atmosphere which is our birthright.

Canon C. T. Wakeham: My house is an 8-roomed bungalow, and electricity is the only form of energy and light used in it. The cost of electricity in 1925 was £49 for power and heating. Look what is added to our comforts, and to the health of the household by having electricity. There is no sweeping brush in the house, and no scrubbing on hands and knees. We enjoy perfect ventilation; there is only one chimney in the house and the Dean of Guild made us put this up before he would pass the plans. There are only four persons in the house, including a maid, but there is nothing very much to do; with the exception of washing and bed-making, everything is done by electricity. We have several plugs in every room. My hot-water supply costs me only 1s. 3d. per week, the electric heating element being switched on continually. My electricity bill for the period 5 November–9 February—the 3 heaviest months—averages £5 per month, and we have had nothing but comfort. I have nothing but praise for the electric house.

Mr. A. B. Munro: The question of the all-electric house is not a new one. For instance, in the all-electric scheme at Hazelwood, Dumbreck, about 16 houses were built on the all-electric principle in 1914. There have been many changes in the ownership of these houses, mainly on account of the unsatisfactory working of the electrical installation and the cost of operation. The original cookers supplied in these houses have been removed and cookers of a new type supplied by the Glasgow Corporation free of charge, to beat competition from the local Gas Department, who were requested by the tenants to give a supply. I have lived in one of the larger houses of a Glasgow Corporation housing scheme, equipped for all-gas working. The installation consisted of 4 gas fires, 15 lighting points, gas wash-boiler and circulator. The operating costs worked out at 9d. per day. From the figures which have been produced for all-electric working, I only wish that gas consumers were as easily satisfied as electricity supply consumers seem to be. Whatever electricity can do, gas can do at one-third of the price. I calculate that to produce the electrical energy required in a house such as that described by the author would require the consumption of something like 18 tons of coal at the generating station. That may be a conservative estimate, but on the other hand it may be an overestimate. From the national point of view I think that that is a useless waste of national resources. Electric generating stations can show a thermal efficiency of only 12 to 18 per cent. There is surely something wrong when a great industry is allowed to use up coal in such a careless and wasteful manner. The vacuum cleaner is useless and inefficient; the work can be performed infinitely better by hand. The electric clothes-washing machine is only suitable for those who do not dirty their clothes. If clothes are to be made white they must be boiled and bleached in the sun or by chemicals. The method described by the author for the lagging of hot-water tanks is excellent. There is nothing like healthy rivalry to encourage improvements and make for better service in both the electric and gas industries.

[The author's reply to this discussion will be found on page 790.]

Mersey and North Wales (Liverpool) Centre, at Liverpool, 19 April, 1926.

Mr. H. Dickinson: The general public always have the idea that electricity is so very expensive, but if the tariffs are right, as they are in many towns, the cost of electrical operation in a house is not the serious matter it is generally supposed to be. In the early days the argument now raised as to cost of using domestic appliances was used with regard to electric lighting, viz. that electric lighting was so very costly that it was impossible to use it. These views have gradually been dissipated by experience and I feel that the same thing will apply with regard to the use of electricity for domestic purposes. The author has mentioned that the cost in Glasgow is too high, but I do not agree that cost is the all-important matter. Greater convenience and comfort usually cost more, and I think that is the case with electricity. Very few people know what amounts they pay at present for coal, gas and light, and if they have to pay more for electricity they think they cannot afford it. Domestic service at the present time is a great deal more difficult, the cost of that service is great, the maids must have more freedom, and consequently the lady of the house has more work to do. By using domestic appliances she can save herself labour, get the house work completed in the early part of the day, and thus have more time for recreation and amusement. With regard to the cost of building the house, I was rather surprised that the author thinks the cost will be from 3 to 4 per cent more than that of an ordinary house. From some calculations which we made we came to the conclusion that if the house were designed as an all-electric house it could be built at a less cost than an ordinary house. The author has put in his house certain things that would have been unnecessary if he had been quite satisfied that the all-electric house was going to be perfectly successful. For instance he has put in chimney breasts and so on. The electrical installation is much more elaborate than under ordinary circumstances but I think it is advisable in order to allow apparatus of ample size to be used. I quite agree with him as regards the convenience and quality of electric cooking, and there is no doubt that his new

cooking utensils give an increased efficiency, but I am rather doubtful whether in actual practice that type of apparatus will not cause a considerable amount of trouble. If he can prevent the pots boiling dry, well and good, but I am a little doubtful and I am afraid he may have some trouble with connections to the pots as shown. One essential thing in connection with the use of domestic appliances is a good maintenance scheme. If many ovens are running on the system they must be well maintained. Boiling-plates also give trouble, but a good maintenance system minimizes the trouble to a very large extent, and I have no doubt that boiling elements will be very considerably improved. At the present time we are testing out a new type of element for which we hope to give at least a 2 years' guarantee, and we hope to be able to give a higher loading on the element than has been possible up to the present on the size that we have to use with ordinary cooking utensils. The hot-water system adopted in Glasgow is an ideal one from the supply point of view, but I do not think it will be satisfactory under ordinary conditions. It may be satisfactory in the author's case, where he turns the switch on in the evening and off in the morning, but not every one will do that. Then again the author has to use a very big cylinder; if a house is specially built provision can be made, but in an ordinary house it is difficult and in many cases impossible to install a cylinder of that size. We have therefore to be content with a smaller cylinder and are driven to look at the question from a different point of view. I should imagine that many times when the demand for hot water is above normal the temperature must fall very materially, and that there will be times (other than non-peak times) in an ordinary house when the 2-kW heater at the top of the cylinder has to be used. We are experimenting in Liverpool with the electrical heating of water. In each of 160 houses there is one small element running continuously through the 24 hours to cover radiation losses, and a larger element controlled by a thermostat raises the water to the required temperature. We may not get such a good load factor as the author gives, but the results are very good, not only from our point of view but from the consumers' as well. It is very encouraging to find that some of the consumers who have had experience of the system are recommending their friends to try it. In connection with the Corporation housing schemes four all-electric houses have been erected, three of which have been tenanted about one month. Another 250 all-electric houses are under construction. No provision whatever is made for the use of coal in these houses.

Prof. E. W. Marchant: The use of radiators is the first point to which I should like to refer. Many people have told me it was impossible to get enough heat from electric radiators. The reason was, of course, that the radiators were not big enough. We find that a 3-kW radiator in a room about 26 ft. × 22 ft. is ample. I had this fixed in the fireplace and so arranged that it could be taken away and a coal fire put in when it was wanted: we have only used the coal fire *once* during the winter. The second point is with regard to cooking. We have found cooking by electricity more satisfactory than any other method. The chief difficulty has been with the boiling-plates, the renewal of elements in which is, I think, likely to be a fairly heavy charge. I think boiling-plates are, however, superior to the special utensils the author uses. I am afraid there will be a great deal of trouble with the plugs on these utensils, as well as trouble due to the heating elements burning out when there is no liquid in the vessels. I do not think boiling-plates are quite so inefficient as the author states. We obtained an efficiency of over 40 per cent in some tests which we have made. The boiling elements are certainly the weakest point in the electric range, and that brings me to the point which Mr. Dickinson has mentioned, viz. maintenance. If there is any trouble with the boiling elements, we ring up the Corporation Electricity Department, and a man comes and puts them right. Unless there is an efficient system of maintenance in connection with electric cookers, I am sure the electric system will not be a success. As regards cost we have not a very long experience, as an electric cooker was installed only last September. We are still using a hot water boiler which burns coke, and I think there is some advantage in having one fire left for burning rubbish. Our consumption of electricity is from 7 to 8 times what it was in previous years, but the total cost for coal, gas and electricity, as far as I am able to judge from two quarters' bills, will be no more than it was previously, and, of course, the saving due to the absence of coal smoke and ashes is very substantial. A further advantage is the insurance against the stoppage of coal supplies due to strikes which the use of electricity provides.

Mr. A. S. Wilson: I feel that the author has proved up to the hilt his case that the all-electric house is a practical possibility and almost a necessity. I feel that we can now spend our time to the best advantage by seeing how this service can be handed on to all sections of the community. The tariff available to the author was a favourable one. I have been making a few inquiries with regard to the annual cost involved in average houses now using coal, gas-cooking, and electric lighting and heating and I find that on the basis of a probable consumption of about 10 000 units per annum the all-electric change-over would be a commercial proposition, apart from the advantages to be obtained in labour-saving, cleanliness and general convenience, etc. One of the most important things mentioned by the author is the insignificant cost of lighting which has been made so much of in the past; the main advantage to the consumer is now to be looked for in the adoption of electricity for cooking and heating. The author's wiring arrangements are certainly very elaborate, but there is one point which I feel should be stressed, that is, the example he has set in regard to the ample provision of plug points throughout the house for the convenient placing of portable electric fires, etc., to meet varying conditions in the home. Figures recently published show that we are very much behind other countries in regard to the number of units used per head of the population, and the author has shown how this state of affairs can be remedied to the advantage of all concerned.

Mrs. H. Dickinson: I imagine that the author's saucepans are very heavy to lift in order to turn the contents out. I certainly think that the hot-plate is not quite as efficient as it should be. Many people think that it is difficult to cook by electricity, but my experience is that it is much easier to teach even the most inefficient girl to cook by electricity than it is to teach her to cook by gas or by coal. We find that food cooked electrically tastes much better than that cooked by ordinary means. In regard to radiators, in an all-electric house it is very much easier to heat a room by electricity, owing to the fact that the radiators can be placed in any position and also owing to the ease with which the temperature can be regulated. I quite agree with the author that it is radiated heat, not hot air, that is required.

Prof. F. J. Teago: The annual costs given by the author and by Mr. Hague tend to show that, provided the tariff is right, the all-electric house is already within the means of even the small-income household. Personally, I have never yet been in a position to contemplate an all-electric house, but I have had experience of a house where only coal was available for the usual domestic requirements, and only paraffin oil for lighting. This particular combination of coal and oil possibly represents the cheapest money payment, and the dearest labour payment proposition that it is possible to obtain (what one cannot pay for in money must be paid for in labour), and the total annual cost was £15; the household consisted of three persons and no maid was kept. It is comforting to find that Mr. Hague's annual cost for his all-electric flat is also practically £15, and that for the same money payment he obtains all the required services with a minimum amount of labour. I am not of the opinion that, had Mr. Hague's household consisted of three persons instead of two, this annual cost would have been appreciably greater, provided that the extra person was not a maid living in. The author does not say whether maids, living in, are included in his household of six persons; but assuming they are, then since the maids must have light and heat, etc., the household is virtually doubled, and each part costs approximately £22 per annum, which compares favourably with Mr. Hague's cost of £15, since the author's household consists of a greater number of persons. The point I wish to make is that it is not so much the number of rooms in a house nor the number of persons forming the household which matters, but that the number of sections into which the household is divided is the important point. I feel that the Institution would be doing a great service to the electrical industry if it would collect, classify and publish statistics of the annual costs of all-electric houses, so that the general public could be supplied with some idea of the probable high and low limits within which their costs would fall in the event of their becoming owners of all-electric houses.

Mr. A. W. Lewis: I agree with the last speaker that architects are often called upon to electrify existing houses, which is a more difficult thing to do successfully. None of my friends who use electricity for cooking would go back to any other method. It can be argued, however, that the most economical use of coal is to convert it into gas and use this for heating and lighting.

Mr. J. W. Gibbs: I have recently installed an electric cooker in my house, and I am trying gradually to convert the house into an all-electric one, but I think that the maids will insist on using their kitchen fire as well. I should like to ask the author one or two questions. Who switches off the heater from the hot-water tank when he is away from home? What does he consider to be the correct temperature for a sitting-room? I am afraid that radiators are open to the same objections as an open fire, i.e. the person becomes very hot on one side and very cold on the other.

Mr. H. C. Hazel: The data contained in the paper should be valuable as a reference to members of the electric supply and contracting industries, who are daily asked by prospective consumers what their annual charges will be for electricity in the event of their equipping their houses for light, heat, cooking, hot-water service, etc. The usual questions asked by a prospective consumer are:—"What are the charges, i.e. the cost of electricity per unit?", "What would be the approximate all-in cost per annum?", and "What would be the cost of installation?". One of the reasons, I think, why electricity is not made use of, especially in homes, to the extent that it should be, is the complicated methods of charging which the supply undertakings have instituted. Glasgow has a system of standard charging based upon so many units (M) at 4½d. per unit plus ¾d. per unit thereafter, and those M units are the estimated annual consumption for lighting and include the consumer's share of capital and fixed charges. From this it would seem that each consumer must be separately assessed by the supply undertaking to fix the value of M. In Liverpool and other towns the rateable-value method has been instituted, this being a fixed charge of, say, 20 per cent of the rateable value of the house, and all the units consumed are supplied at ½d. per unit. In my opinion neither of these methods is clear to the layman and neither gives any definite indication as to what would be the approximate cost per unit to a person who proposes to build a house in any district, as on the rateable-value method the house would not be assessed until after it was built. For a house where a full use of electricity is contemplated, I suggest that a more simple method would be a fixed amount per annum for each living-room. This would not include cellars, lavatories, pantries, bathrooms, etc. Such an amount could be fixed so as to bring in a sum to cover the standard charges now received by the other methods, plus actual units metered at ½d. per unit, and would certainly be easier for the man in the street to grasp. The author has been fortunate in being able to collaborate with his architect, so that provision has been made in the layout of the house for all his wiring runs. This is a decided advantage, helping to cheapen the installation and at the same time minimizing fire risks and maintenance charges. Architects generally should co-operate more fully, when building houses, with the different specialists as to their requirements. These specialists are, as a rule, only called in when the house is almost completed, in fact just before the plastering

is to be commenced, thus causing unnecessary cutting away, etc., which adds to the cost. I think that the author's selection of C.T.S. wiring is quite a good one, especially as provision for suitable runs had been made in the house, but as no figure is given as to the cost of the wiring installation, no criticism can be made. What is the size of the service mains to the house, and what has been the maximum current noted at any one time? I note that the main switch is a 50-ampere one, and this seems to be on the small side. I should further like to ask if each room has its own radiator or if only a limited number of radiators are used and carried from one room to another. I note that the author is not satisfied with the boiling-rings, and this opinion is more or less generally held. I have installed a number of cookers, and in every case complaints have been made about the cost of boiling vegetables, etc., on the rings. I think that the only solution is to have, as the author suggests, the heating element embodied in the cooking or boiling utensil, as in the case of a kettle. The conclusions arrived at certainly show that the "all-electric" house, with electricity at an average of ¾d. per unit, is an economical proposition as compared with coal and gas, while at the same time it must show considerable saving in labour and be far more healthy. The data given should be the means of influencing many to electrify their houses on similar lines to that of the author.

Mr. P. J. Robinson: For the past two years I have occupied an "all-electric" house, but I have not had the advantage that the author has had, for I have had to convert a coal-fired house into an "all-electric" house. This has been done largely by placing radiators in the existing fireplaces, and open vents into the flues for ventilation purposes. It would appear, by comparison with figures given by the author, that my house is about 10 per cent larger than his, and the cost to me worked out last year at £51, the consumption being approximately 21 200 units. This figure is in excess of what it might have been, but a certain amount of experimental work has taken place, and these units are included in the total. The water has been dealt with by putting a constant loaded heater, controlled by thermostat, in the existing water tank, the capacity of the heater being 720 watts and of the tank 32 gallons. We have had an ample supply of hot water for all the usual purposes, but of course this does not allow more than one really hot bath a day, which on an average is sufficient for a household of 5 people. It is interesting to note the apparently good example that I have set in the immediate neighbourhood where I live, as evidenced by the number of people adopting electricity for their main uses, as 11 houses within a radius of 100 yards or so have practically been made, or are in the process of being made, "all-electric." Comparing the year 1922 with 1925 the units consumed in these 11 houses have already increased from 3 200 to 70 600, and the latter figure, showing an increase of 2 100 per cent, is rapidly increasing. On an output of this number of units, the capital charges on the distribution in this immediate district sinks to a very small figure. As mentioned by Mr. Dickinson, we are at the present time electrifying a number (some 250) of Corporation houses. We estimate that the total number of units used in these houses per annum will average 6 000 per house, which at the rate of charge of 2s. weekly plus ½d. per unit consumed, measured by means of a 1s.-in-the-slot meter, will amount to an average cost per house of 6s. 9½d. per week. I have obtained some statistics from a number of employees in the Department who live on existing Corporation estates, some using coal and gas, some gas alone, some gas, coal and electricity, and some electricity and coal; and from a group of 11 houses I find that the average cost per week is normally 7s. 4d. per house. This, of course, covers lighting, coal and gas bills. It will be interesting to see whether our estimates in the "all-electric" houses is correct or will be any greater than this, but we have estimated on the basis that water-heating will take 2 400 units, the allowance being 24 gallons of hot water per day, the mean temperature being 136° F. This is with a loading of 300 watts (continuous). These tanks are supplied with thermostats, as although thermostats tend to decrease the load factor they prevent any waste of energy if less than the stated amount is used. From the above it will be noted that the costs approximate very closely to the author's figures. I am glad to say that the architects have allowed us to collaborate with them in the design of the house. Ventilation has been provided by means of ducts discharging into the roof from each of the rooms, with hit-and-miss ventilators both on the outgoing duct and the incoming duct in the outer walls of the house. With regard to the hot-water supply, the hot-water loss in these houses has been carefully considered. There are three points of hot-water supply, wash-hand basin and bath, and the washing-up sink in the scullery. The losses in the pipe from the hot-water cylinder, which is situated on the wall between the wash-basin and the bath, are as follow: To the wash-hand basin 0·41 pint, to the bath 1·22 pints, and to the sink in the scullery 0·82 pint. Without a system of remote control I do not think it is possible to reduce this loss any further. One of the difficulties of electrifying an existing house is the enormous loss between the heating cylinder and the point at which the hot water is taken off. In some cases it amounts to 2 gallons. I am in agreement with the author that one of the principal defects of an "all-electric" house appears to be the somewhat unreliable nature of the electrical gear produced at the present day. We have tried a great number of experiments with a view to improving the reliability, and the boiling-plate referred to by Mr. Dickinson will, in my opinion, overcome many of our difficulties. Open-type boiling-plates are, in my opinion, highly undesirable, as they are liable to be damaged if milk or fat is spilt on them. In addition, if, say, a fork is accidentally dropped across an open element and the oven casing, a short-circuit is caused. With regard to the appliances with their own built-in element, one of the difficulties that seem to be almost unsurmountable is the fact that if any of these appliances are allowed to run dry they will have to be renewed, and this gives rise to an additional expense which is to be avoided in efficient service. We have, at the present time, succeeded in getting a satisfactory

element of 1 800 watts into an 8 in. × 8 in. square plate, and we are in hopes of getting one of 2 250 watts into the same area. Incidentally, with reference to the author's remarks on page 294 with regard to the lagging of tanks, cork is very expensive and we have found corrugated paper, similar to that used for the packing of bottles, placed against the tank and covered with ⅝ in. thickness of felting with canvas sewn over, the whole being finished with a varnish paint, is very efficient. In the Corporation houses an aluminium cover is being substituted for the canvas.

The Author's Reply to the Discussions at Newcastle, Glasgow, Edinburgh and Liverpool.

Prof. S. Parker Smith (*in reply*): In response to numerous requests for a daily load curve on a winter's day, the Glasgow Corporation Electricity Department have kindly taken the graph shown in Fig. C (p. 791), which may be compared with Fig. 8 in the paper for a summer's day. By a peculiar coincidence it so happened that, when this graph was taken, the kitchen fire was not in use that evening, as the maids were out; consequently the evening load should be increased by 8 amperes (2-kW fire).

In order to demonstrate the feasibility of artisans' all-electric dwellings, the details referred to in my earlier reply (see page 330) have been elaborated in an article in the *Electrician* (1926, vol. 96, pp. 346 and 354). The revised figures are based on a 10 per cent higher consumption, and it is concluded that with energy at ½d. per unit plus a fixed charge the proposition is sound.

In order to avoid repetition in the present reply, the earlier reply on page 328 should be consulted.

Newcastle.

The long experience of Mr. Pinkney is valuable, particularly in view of the less favourable tariffs in his area. With the tariff prevailing on the Newcastle Electric Supply system, a lagged tank would seem to be imperative. The two-rate meter may not always be justifiable, but is undoubtedly so in the speaker's or the author's house. As regards expense, it should be remembered that some supply undertakings fit two meters (for lighting and for heating) even in small houses.

Mr. Clothier's remark regarding efficient domestics is appreciated, and a wider use of electricity would both ease the situation and provide efficient service. It is difficult to see why electrical appliances should not be used in bathrooms, provided they are effectively earthed. Though the use of plugs as switches leads to economy in house wiring, and is not only sanctioned but adopted by some supply undertakings, the practice is risky and might lead to bad shocks and burns and rapid deterioration of the contacts. Even if a switch is provided on the appliance, there is nothing to render its use imperative, nor to safeguard the operator when plugging in in the event of a short-circuit. Clearly switchplugs to be effective must have mechanical interlocks to ensure correct use.

Mr. Ward's contentions are mainly ill-founded. The number of heating points is not excessive—many are now duplicated for convenience. No discomfort whatever is experienced on washing-days. The cloak room is for cloaks. The distribution board is in a convenient position where it is and would be inconvenient in the cloak room. The use of split conduit was ruled out from the outset, though a length of open conduit is useful where there is a danger of driving a nail into the rubber covering. The effectiveness of the drying closet is largely due to the vigorous supply of air drawn through it. As regards boiling-plates, the first preference is to avoid any type whatsoever, the second is the closed type, because it is safe though slow. It is hoped that the results obtained on boiling-plates will soon be published. None of the anticipated drawbacks of self-contained vessels were realized. I disagree with most of the speaker's views on hot-water supply, ventilation and room-heating. No auxiliary apparatus is used on the lighting circuits.

Many of Miss Holm's suggestions are helpful. Perhaps the washing machine is superior to the boiler, but it is much more costly to buy. Experience has proved the feared drawbacks of self-contained cooking vessels to be illusory, but it will be noticed that a boiling-plate is provided in the proposed arrangement in Fig. A, p. 330. Among the many desirable but not essential appliances installed, an electrically-heated towel rail has been included. The suggestion for preventing garbage becoming a nuisance is useful. Speaking generally, the all-electric house appears to greater advantage where no domestic servants are employed.

The only reply to Mr. Gregory, beyond saying I do not agree with him, is that I have never lived under less barbaric conditions than at present. The rooms are not chilly—perhaps on account of the hollow walls—and the members of the household neither complain of cold nor do they catch cold. My one grumble is that I have to work in a centrally-heated building; and I have no wish to transfer the discomfort of warmed air to the home.

To Mr. Cross I would say that the under-running of the lamps is less than he assumes. Instead of 250 volts, the lamps are rated for 260 volts—this is also advisable in case the supply voltage rises above its declared value. Mr. Cross agrees that one need not be specially careful in the use of current for lighting; all the more reason therefore to pay due regard to the life of the lamps. I do not agree with the view that the bulk of the standing charge should be debited to lighting—electrical energy should be used freely for lighting. The practice of using electricity solely for lighting ought not to be allowed to govern tariffs for the general case.

In reply to Mr. Williams, the absence of a coal fire in the kitchen has not caused any trouble with domestic help—rather the contrary. The figures in Table F will be appreciated. Whilst the annual cost is similar to

my own, it will be seen that electricity works out at about 2d. per unit. At this price it is seen that the all-electric proposition would be ruled out on a cost basis.

Glasgow.

Acknowledgment has been made in the paper to Mr. Mitchell for his hearty co-operation and pioneer work in domestic electrification. His argument should appeal to many supply undertakings and it is hoped that low-temperature carbonization at the power house to which he refers will soon permit further progress to be made in the reduction of tariffs.

Mr. Robertson has made an interesting contribution. The omission of a sun bath is admitted. The house was not built as an institution, but a sun bath can be installed if required. The liberal provision of heating points has proved a great benefit; also running a separate circuit for each point has many advantages. The figures in Table H are informative, by showing the difference made by coal fires. It will be seen that increasing the consumption from 2 824 units to 4 586 units caused the average overall cost per unit to fall from 1·2d. to 1·1d. Had the running costs been based on Glasgow tariffs, and the standing charge kept the same, viz. £6 10s., the total cost with coal fires would have been £23 1s. 8d. and with coal fire for heating water only, £22 1s. 1d., while the overall cost per unit would have been 1·05d. and 0·84d. respectively. This emphasizes the importance of cost; also the feasibility of electricity for domestic heating.

The particulars given by Mr. Hardie are very welcome. Not only can he speak authoritatively on all forms of electric appliances for the home, but he has shown how the overall cost per unit at the Glasgow rates can be made as low as 0·656d.

Edinburgh.

Prof. Baily made a long contribution to the discussion and I can only regret to state that I am in profound disagreement with him on almost every point and particularly on questions of fact. To assert that the warming of the rooms and the amount of hot water correspond to the mode of life in a small flat is as far from the truth as to assert that to live in an all-electric house is to live in the lap of luxury. Prof. Barker's figures in Table A on page 305 prove that the net B.Th.U. used per person per annum are quite normal, while ample evidence has been given to show that the costs are reasonable. Apparently the points of view are fundamentally different, for I attach great importance in the home to economy in worry and drudgery as well as in money. The leisure obtained thereby can be fully occupied by the more desirable things in life. I fail to see the object of air-heating tests with radiant fires. No dampness has been observed.

In his criticism of the low rate for heating water during night hours, I think Mr. Seddon fails to attach sufficient importance to the actual conditions. Properly considered, the domestic tariff in question is really a three-part tariff: the fixed part, the part at ½d. per unit, and the part of ⅜d. per unit. Thus the consumer's share of the fixed charges has already been met. As

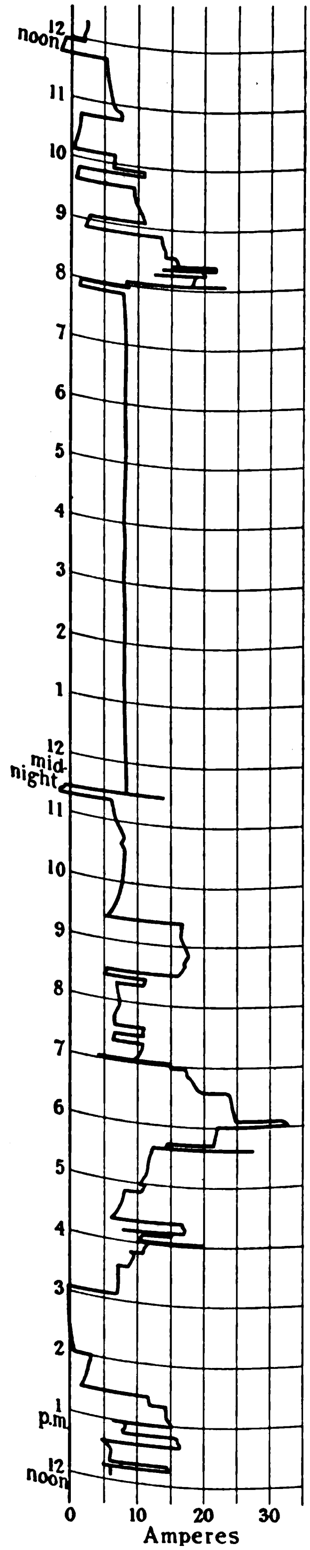

Fig. C.—Load curve for Tuesday, 16th February, 1926. Mean height = 8·69 amperes.

regards differentiation, does not Mr. Seddon make consumers at peak hours, i.e. the lighting-load consumers, pay a price corresponding to his costs in one way or another? Similarly for low-power-factor consumers.

Replying to Mr. Duncan's remarks, it would be a simple matter to arrange for portable lights in the bedrooms. Also the wash boiler can be replaced by the more costly machine, if desired. The connections are as stated, but it was not deemed necessary to make alterations after the experimental period was completed, as the matter was too insignificant. In a new layout, of course, the necessary modifications would be made. A proper appreciation of the unassessable advantages of electric working is important.

Mr. Sharpley has kindly given us his own costs. I need but repeat that ample evidence has been given to show that the Glasgow rates are comparable with rates for other modes of heating, etc. Many members will agree with the comments on the wastefulness of maids—the all-electric house naturally appears to the greatest advantage where no maids are kept. The tank lagging is cork. A fireless electric cooker has been tried. It seemed satisfactory, but could not replace the ordinary oven and utensils.

The only comment I have to make on Mr. Mears's remarks is that the small house will probably feel the advantage of all-electric working before the large house.

Mr. Martin has given a good analysis of the supply position regarding the heating of water. The substitution of C.T.S. wiring for screwed conduit should not only result in lower installation costs, but prevent much damage to old houses being wired. The modern method has other great advantages in house wiring.

Canon Wakeham's experience is valuable, more especially as it comes from a "layman" in matters electrical.

It is not surprising that the cookers supplied in 1914, referred to by Mr. Munro, should now have been replaced. I do not dispute the estimate for coal consumption. This point is dealt with in the paper (page 298). Possibly some low-temperature carbonization process may be developed for power stations. But even under existing conditions, modern power stations can produce energy at a competitive price. If one speaks of the useless waste of national fuel, what is to be said of the coal fire, which produces smoke in addition? In any case, the coal trade cannot complain in this respect. There is no need for me to champion the vacuum cleaner or the washing machine. Enough evidence in their favour has already been given in these discussions. If anyone has a right to complain it is the supply undertaking, on account of the small current consumption of the apparatus, or the consumer on account of their initial cost.

Liverpool.

Mr. Dickinson has rather misconstrued my remark that the cost in Glasgow is too high. As many speakers have shown, the cost as it stands is competitive; also full weight has been attached to convenience and comfort. Many people, however, are not prepared to take the latter for granted, particularly in view of the capital outlay required for conversion. Consequently the all-electric proposition will become more attractive when it can be definitely shown to be cheaper than any of its alternatives. It is not intended to convey that every all-electric house will cost 3 to 4 per cent more than an ordinary house. Chimney breasts are not essential, but the flues are good ventilators. Regarding the pots with self-contained elements, it need only be said that three months' experience with them is sufficient to make a return to boiling-plates unthinkable. A combination of speed and safety with a saving of 50 per cent is ideal for the consumer, however the supply undertaking may regard it. All the switching for hot water can be done automatically. The water temperature falls very little, as the incoming water mixes very slightly. Actually the emergency heater is seldom needed, and never during peak hours. It is very encouraging to learn that all-electric houses (where no coal whatever is used) are being built in Liverpool.

The weakness of the boiling-plate is indicated by Dr. Marchant, but he does not draw the natural inference. Whilst it is agreed that electric cooking would not be a success, without proper maintenance by the supply undertaking, is it not equally certain that high upkeep will ultimately prove prohibitive? None of the anticipated troubles with the self-contained utensil, such as boiling dry, has been experienced by me. An efficiency of 25 per cent would be a fair average to take for domestic-type boiling-plates.

The remarks made by Mr. Wilson are very encouraging, but more will have to be done to assist wiring and improve appliances, especially cookers, before the all-electric house can be expected to become general.

In reply to Mrs. Dickinson, it might be said that the pots with built-in elements need not be heavy —my own, though substantial, are no heavier than pots for the coal range.

The point made by Prof. Teago regarding the number of rooms in use simultaneously is important. In my house, a living-room and kitchen were always in use.

The conversion of existing houses to electric working, referred to by Mr. Lewis, need not be difficult, provided use is made of the more modern methods of wiring. It is possible to push the argument of the most economical use of coal too far. After all, the importance of obtaining from coal what is required ought not to be lost sight of.

The point raised by Mr. Gibbs regarding a coal fire in the kitchen has not arisen in my house. Any person in the house can operate the tank switches—there is no more difficulty here than with a fire. A sitting-room where the persons are well supplied with radiant heat can have a temperature of 50–55° F. With the electric fires properly placed there is no question of one side of the person getting too hot while the other side is left cold.

With reference to Mr. Hazel's criticism of the methods of charging, doubtless much could be done towards simplification and standardization. The two-part tariff is a fair one in principle, and it can be easily explained to the layman. Basing the fixed charge on the number of rooms is a well-known system; but, generally speaking, with the same price per unit the overall cost per

unit does not vary much with any of the systems in vogue. There is a decided advantage in collaboration between architect and electrical engineer—this is practically essential if the best results are to be obtained. Certainly the wiring should be done before the plastering in a new house; even in a house under conversion the amount of cutting away should be reduced to a minimum. The current reached can be estimated from Fig. 8 in the paper and Fig. C on page 791. Generally speaking, most rooms have their own radiators, but occasionally a radiator is carried from one room to another.

The figures given by Mr. Robinson will prove very encouraging to many of his colleagues in other towns. His overall cost per unit of 0·58d. is admirable. The estimated consumption of 6 000 units per annum compares well with my figure of 5 500 units; also the predicted costs agree closely. The result will be watched with interest.

Results of Second Year's Working.

It is hoped to give the requested figures for the second year, ending 10th July, 1926, in a later reply. It can already be stated, however, that the total consumption will be slightly less than in the first year; the heating consumption will be higher, on account of the severer winter, but on the other hand the cooking consumption will be lower, due to the use of utensils with self-contained elements.

PROCEEDINGS OF THE INSTITUTION.

737th ORDINARY MEETING, 21 JANUARY, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 7th January, 1926, were taken as read and were confirmed and signed.

Mr. H. L. Leach and Professor J. T. MacGregor-Morris were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:—

Elections.

Member.

Stanhope, Joseph Henry.

Associate Members.

Aust, Frank, M.Sc.
Beck, Edwin La Touche.
Burke, Reginald Thomas.
Dalby, Joseph Francis.
Ewart, George.
Flanagan, Patrick, B.E.
Flockhart, Derwent Pearce.
Goatley, Anthony Horace.
Greenwood, Harold Jackson.
Hall, Roger Vine, B.E.
Hirsch, Paul Bernhardt.
Jones, Nelson.
Kearsley, Frederick William.
Land, Alfred Edgar.
McAlonan, Francis Wilson B., B.Sc.(Eng.).
McMillan, Daniel.
Mitchell, Alexander Stewart.
Newman, John Ernest.
Plowman, William Ewart.
Schofield, Harold Hubert.
Shackell, Reginald Walter.
Stretton, Leonard Wilfred.
Sutcliffe, Gilbert George.
Tuck, Harry Playford, B.Sc., B.E.
Turner, Philip Keston.
Waters, John Henry.
Withycombe, Robert.
Yorke, Gerald.

Graduates.

Agate, Purushottam Narayan, B.Sc.
Ahmed, Hussein Mohamed.
Almond, John.
Ambalavanar, Pasupathippillai.
Amies, George.
Beale, Robert Talbot G. C.
Brown, David Gregory, B.Sc.
Brown, Edwin Lionel.
Bull, Robert.
Campbell, Archibald Stewart.
Campbell, James Philip.
Carter, Frank Alexis.
Chantrill, Ralph Lohbek, B.Sc.
Christie, Thomas Gregg, B.Sc.
Clark, Douglas Gordon.
Colson, George Basil.
Crowley, Cornelius.
Dobell, Claude Herbert.
Dore, Claude Urling.
Dunn, Leonard William.
Ely, Eric Stanley.
English, Harold.
Fisher, Henry.
Gilbertson, Frederick James.
Griffin, Reginald Michael J.
Groeneveld, Raymond.
Guthrie, James.
Hall, Cecil Stuart.
Hall, James Owen.
Handley, William Cecil, B.Sc.Tech.
Hardwick, Charles Philip.
Harrison, Reginald Henry.
Henning, Arthur James.
Hill, Albert Rowland.
Jackson, Arthur Gladstone.
Jarvis, Harry William.
King, Wallis Lovell.
Kitchen, Harold Jennings.
Krishna, Rama.
Kuperman, Moshe, B.Sc.Tech.
Law, Joseph.
Logan, Alexander.
Lown, Stephen John.
MacMicking, Julius Manus.
Mann, Samuel Alfred.
Meldrum, Francis Arnold.
Munn, Herbert Seymour.
Myers, William Henry.
Nuesch, John.
O'Farrell, Joseph P.
Orr, James.
O'Sullivan, Bernard Joseph, B.E.
Parry, Herbert Percy.
Pearson, Stanley Garnett.

Graduates—continued.

Petrides, Sophocles A., B.Sc.Tech.
Phœnix, William.
Pimley, Gordon Haldane.
Pollock, Wallace.
Reddyhough, Harry Lythgoe.
Rees, Horace Edward.
Ripley, Ronald Vincent.
Roberts, Frank Rob C.
Rouse, Wilfred Sydney.
Rudra, John Jitendranath, M.A., B.Sc.
Russell, Edward Powys.
Sankey, George Henry, B.Sc.(Eng.).
Sargent, Hugh Hamilton.
Seaborne, William.
Segrave, Michael.
Shanly; Leo Dennis.
Shelley, George Henry L.
Smith, Arthur McDonald.
Sreenivasan, Kasi, B.Sc.
Stafford, Charles Henry.
Telemat, Shafic Mustafa.
Ward, John Hunter.
Widgery, Robert George.
Woodland, Reginald.

Students.

Ahmad, Ghulam Aziz.
Ainsworth, Frank Glave.
Ambler, Alec Guy.
Ambler, Eric Clifford.
Arnold, Sidney Roger.
Ashcroft, William Alfred.
Austin, Basil Brougham.
Austin, Neville Sydney.
Baker, Edward John.
Ballantyne, Walter.
Baly, Wilfred Frank.
Bamford, William.
Barnard, George Philip.
Barrett, Arthur Edwin, B.A.
Barron, Donovan Allaway.
Barton, Henry Leslie.
Barton, Richard Bernard.
Baskett, Charles Arden R.
Batra, Rajindra Nath.
Beach, Noel Henry A.
Beanland, Charles Percy.
Beckett, Charles Stephen.
Beckingsale, Alfred Alec.
Bedwell, Albert Vernon.
Beetlestone, Andrew.
Bell, Charles.
Bennett, Clayton.
Berens, Cyril Eustace.
Berriman, Leslie.
Bisley, Eric.
Blandford, Ewart Alfred G.
Bolt, Frederick Denis.
Booth, Joseph Westwood.
Bowen, William Looker.
Bradfield, Geoffrey.
Bray, Alan Ison.
Bray, Frederick Harry.
Brett, Edward James.
Broadbent, Maurice Edward.
Broadhurst, Jack.
Bromige, Ernest William.
Burton, Gordon Victor.
Butters, John Arthur.
Calder, Alexander, B.Sc.
Calder, Rex Finlayson C.
Cameron, Thomas Tennant.
Canter, George William G.
Cartwright, Arthur Henry.
Castellan, Guy Edward.
Chakravarti, Jogendra Narayan.
Chanter, Arthur John, B.A.
Chapman, Leslie James.
Chapman, Ralph Eustace.
Chapple, John.
Chard, Frederic Delacourt.
Christmas, Francis Thomas.
Clarke, Edgar Valentine.
Clothier, George Donald.
Coke, Robert Alexander.
Collins, Herbert.
Collins, William Henry A.
Collyer, James Kimberley.
Coote, Thomas Charles.
Copping, Harry.
Corfield, William Graham.
Cousins, George Jeffrey.
Cozens, Geoffrey Gordon.
Craig, Daniel.
Craige, George Samuel.
Crocker, William Gordon.
Crutch, Leslie Spicer.
Cumberbirch, Alan.
Curley, James Claude.
Daley, Matthew.
Dawes, Eric Arthur.
de Beer, Charles Loxton.
Delmar-Morgan, Edward Locker.
Dew, William Evelyn.
Din, Arthur John.
Donkin, John.
Douglas, John MacGregor.
Dryden, Charles Ernest.
Dudley, Leslie Clarence.

Students—continued.

Dyson, Edgar Veary.
Earle, James Bendyshe.
Eastburn, Harry.
Elson, Mayne Bennett.
Emerson, John Christopher.
Erlangsen, Sidney Johannes.
Evans, Alfred William.
Faragher, Arthur John.
Farries, Herman Ramsay.
Fearnside, Edwin Royden.
Felton, Alonzo.
Fenwick, Arthur Cecil.
Ferguson, Norman Winton.
Fernando, Edmund Clement.
Fielder, Cecil Redvers.
Fordyce, Herbert Nairn.
Foster, John Viret.
Freeman, Cressy Edward.
Gahan, Hugh Leslie.
Gardiner, Stephen Maurice.
Garnett, Arthur John.
Geary, Spencer Fernley, B.Sc.
Gehr, William.
Ghani, Mohammad Abdul H.
Gibbs, George Henry P.
Gibson, Franklin Henry.
Gibson, Gordon.
Gill, William John R.
Gough, Douglas Ernest.
Gould, Ephraim Frederick H.
Goyder, Cecil William.
Graham, David.
Green, John Arthur.
Greenwood, Leslie.
Griffiths, John.
Grose, Francis Reginald.
Gunzburg, Noah.
Hagry, Soliman Aziz, B.Sc.Tech.
Hall, Frederic Philip W.
Hambley, Stanley George.
Hansford, Robert George C.
Harris, William, B.Sc.
Hartley, George Clifford.
Harvey, Robert Antony.
Hastie, John Stewart.
Hawker, Michael Seymour.
Hawkins, Nelson Alexander.
Haynes, George.
Hayward, Edwin James.
Heaton-Armstrong, Louis John.
Henzell, Owen Maxwell.
Hill, Roy Varnell.
Hiller, Reginald James.
Hime, Malcolm William.
Hindley, Frederick Thomas.
Hockey, John Alfred.
Hodgson, Alan D'Arcy.
Hogan, John Ross.
Holdup, Edwin Douglas.
Hole, Edwin George C.
Hollingsworth, Philip Massey.
Holmes, Albert Edward.
Holroyd-Smith, Henry Horace D.
Hopkins, Edgar Hamilton.
Hoptroff, Victor George.
Hopwood, Albert Edward.
Humfrey, Cyril Maurice.
Hunt, George Leslie.
Ingham, Frank.
Ingham, Harry Allott.
Jackman, Arthur John.
Jackson, Bernard.
Jackson, George Edwin.
Jacob, Howard Lawrance.
Jagger, Charles.
James, Gilbert Oliver.
Jenkins, Goodwin Philip.
Jennings, Herbert.
Johnson, Frank Ernest.
Johnston, Robert Galbraith.
Jollyman, Herbert George.
Jude, Harry George.
Keays, Hastings de Jersey.
Keene, Frank.
Keene, Robert Norman.
Kenward, Fred.
Kirschner, Rachmil.
Konried, George Julius.
Lacey, Edgar William.
Lambe, Herbert George F.
Langfield, William Thomas.
Langston, Frederick William.
Law, Lawrence Brian.
Lawrie, Thomas, B.A.
Lay, Edward Henry.
Leadbeater, James Le Butt.
Le Fevre, Richard.
Lester, Arthur Ernest.
L'Estrange, Edwin Layton.
Leung, Francis Simon J.
Lillie, Herbert.
Litherland, Ernest.
Lockwood, Norman.
Lovatt, Cyrus Roy.
Lowe, Harold.
Lowman, Alfred Henry.
Luxton, Charles Edward.

Students—continued.

Lyddon, Percy Edward.
McClean, Frank Whipham.
McCormick, William Harold.
Macdonald, Aubrey John.
McGibbon, Alexander Roxburgh.
McKenna, Peter.
McLagan, Angus John.
McMahon, Thomas James.
McWhirter, William Alexander J.
Maidwell, Cyril Leonard.
Maloney, Stanley John.
Markby, Ernest Joseph.
Marks, Stanley Victor.
Marriott, Ewart Nelson.
Martin, Henry Richard.
Mason, Thomas Frederick V.
Mayo, Edward Alexander.
Mellanby, John.
Mellor, Ramsden.
Messervy, Mary Collette (Miss).
Millar, David Philip M.
Millard, Robert George.
Milner, William Stanley.
Mockett, Herbert James.
Morley, Cyril George L.
Morrell, Francis.
Mortimer, Evan Lennard.
Morton, James Dickie.
Myers, Antony Joseph.
Nadarasa, Ayampillai.
Naismith, James Brown.
Nash, Walter Adlington.
Neal, Harry.
Neate, Eric Charles B.Sc.(Eng.).
Newberry, George Henry.
Noble, James Eastwood.
Overstall, Fred.
Oliver, Alan.
Painter, William James A.
Park, William Edwin.
Parry, Joseph Harry.
Paterson, Allan, Jun.
Payn, Cyril Thomas.
Pearce, Richard Randle S.
Pearson, Geoffrey.
Pellow, James.
Pheazey, Frank Gerald.
Phillips, Cyril Ernest.
Phillips, John William.
Pillai, K. Thiagaraja, B.A.
Piper, Desmond Bamber.
Prime, Frederick William.
Qadri, Noorul Hoda, B.A.
Quantick, Owen John L.
Ralph, Frank.
Randle, James.
Rao, Abludu Ramarao N., B.E.
Rao, C. Setu.
Ray, Satyendra Nath, B.Sc.
Read, Herbert Sidney.
Redman, Richard Henry.
Reid, Donald Geoffrey.
Reynolds, William John.
Rich, George Steer B.
Richards, Harold Giles.
Russell, Douglas Arthur.
Ryan, Hugh Norman.
Salter, Arthur George.
Scott, Colin Methven.
Scriven, Vernon Colin.
Selvey, Arthur Morrish.
Shave, Arthur Ernest.
Shaw, Geoffrey Matthews D.
Shaw, George James.
Shivapuri, Pandit Ratan N.
Shrimpton, Herbert John D., B.Sc.
Shuffrey, Leonard Bentley.
Simpson, Cyril.
Simpson, Geoffrey Arrol G.
Simpson, George Russell.
Sims, Jack Vass.
Singh, Durag Pal.
Skinner, Stuart.
Smith, Cecil William.
Smith, Edward Ethelbert M.
Smith, William Eric.
Snoxell, Ronald Edward W.
Speed, John Flower.
Stamford, Norman Charles.
Stanton, William Alfred.
Staves, Frederick William.
Steele, James Hamilton.
Stephens, Arthur Reginald H.
Stewart, James.
Stoner, Charles Robert, B.Sc.(Eng.).
Stubbs, John Everard.
Stupple, Harold William.
Sumner, John Arthur.
Sutton, Gerald John.
Taylor, Charles Bernard.
Taylor, Ernest.
Taylor, Henry George.
Taylor, John.
Terriss, John Laurleur.
Thomas, Alfred Humphrey.
Thomas, Ronald Arthur.
Thompson, Eric Alexander H.
Thomson, John Lees.

Students—continued.

Toombs, Roy.
Townsend, Horace Ruthers.
Tufnell, Fanshawe Edward S.
Underhill, John Leslie.
Vajramushti, Vyankatesha Ramachandra, B.A.
Veysey, Edgar William.
Voit, Reginald Austin.
Wagstaff, William Percy.
Walden, Harry William W.
Walker, Egbert Ernest.
Walmsley, Francis Charles.
Walton, Ernest Charles.
Warburton, John Henry.
Warren, Sidney Harvey.
Watkins-Ball, Mervyn James.
Welch, Horace Henry E.
Welch, Jack Warwick F.
Wells, William Henry.
Westley, Cecil Frederick.
White, Francis Frederick A.
White, George
White, Gilbert Brandon.
White, Henry Lachlan.
White, John Allan Lawrence.
Whiteside, John.
Wijesinghe, Walter.
Wilcock, Harold.
Wildbore, Wilfred John L.
Wilding, Edward Heywood.
Williams, George Edward.
Williamson, David Blair.
Willis, William Roby.
Wilman, Donald.
Wilson, Charles William F.
Wilson, Roger Walter.
Wishlade, Leonard Carwardine.
Wood, Percival Guy.
Yardley, Albert Arthur R.
Yates, Edward.
Yeeles, Edwin.
Yoganandam, Goteti.
Zambardas, D. Michael.

TRANSFERS.

Associate Member to Member.

Abraham, Robert Morrison.
Blankley, George William.
Boyce, Benjamin Adair M.
Brocklesby, Charley.
Calverley, John Earnshaw.
Cowie, James.
Crawford, John Murray.
Creedy, Frederick.
Dixon, George.
Erlebach, Wilfrid Arthur, B.Sc.(Eng.).
Evans, Cecil Hugh S., O.B.E.
Fogarty, Laurence Francis A.
Fraenkel, Poul Hermann, B.E.
Fuller, Levi Obediah.
Geoghegan, Frederick William.
Harrison-Watson, Raymond Arthur.
Heys, Francis Samuel.
Hitchcock, Edward.
Martin, David.
Mavor, John Bridie.
Morton, James.
Newton, Edwin Isaac T.
Parker, John Hampden.
Poole, William Ernest.
Ritchie, William Andrew.
Rogers, George.
Stockham, Arthur.
Tanner, George Frederick.
Thomson, James Stuart.
Travis, William.
Trippe, Charles Frederick.
Wall, Thomas Frederick, D.Sc., D.Eng.
Watterson, Harold Edward.

Graduate to Associate Member.

Barrs, Herbert Harold.
Bawtree, Edward B.Sc.(Eng.).
Birtwistle, Fred.
Braendle, Ernest William.
Burdett, Edward Priestley, B.A.
Cain, Sidney John.
Campbell, Elliston Fauna, B.Eng.
Clarke, Charles Richard.
Clegg, Percy, B.Sc.Tech.
Conly, William Peter, B.Sc.(Eng.).
Eales, Alfred Billington.
Fiander, Charles Mac.
Flint, Eustace William.
Halford, William Charles J.
Hall, William.

Graduate to Associate Member—continued.

Linsell, Alfred Aubyn.
Loveday, Gilbert Kelsey.
Ostler, Peter.
Pegg, Reginald Noel.
Strand, Ralph Rixon.
Tucker, John Potterton.
Wade, Douglas Ashton L., B.A.
Waring, Alfred James.
Wilson, Maurice, B.A.
Winfield, Frederick C., M.Eng.
Wright, George Thomas.

Student to Associate Member.

Abell, Robert Henry.
Ballard, Frederick Leslie, M.C.
Barlow, Harold Everard M., Ph.D.
Bassil, Richard Whitley.
Brown, Walter John, B.Sc.
Caspar, Frank Albert E.
Clarke, Henry Rowland.
Cooper, Jack Albert, B.Sc.(Eng.).
Dannatt, Cecil, B.Sc.
Donnelly, Wilfrid, B.Sc.Tech.
Fry, Eric Rosewarne.
Harmer, Ernest Walter.
Hogg, Duncan Bardsley.
Holland, William Reginald, B.Sc.(Eng.).
Hutchinson, John Yates, B.Sc.(Eng.).
Jennings, James Smith.
Maynard, William Martin.
Michael, Ernest Frederick, B.Sc.
Montgomery, Alexander William, B.Sc.Tech.
Rawlinson, John David S., B.Sc.(Eng.).
Read, John Carley, B.Sc.
Short, Leonard Highton, M.C.
Thornhill, John Tugwell.
Warren, Alfred Charles, B.Sc.
Whitehurst, John Traill.
Windle, Allan Austin.

Student to Graduate.

Axford, Norman, B.Sc.
Bailey, John Wallis, Captain, R.C.S.
Bamber, Leonard John.
Barfield, Turland John.
Batty, Harry.
Beach, Arthur Ernest.
Beckett, Thomas Rumbold, B.Sc.(Eng.).
Belchem, Robert Henry.
Bhavnani, Hashmatrai Khubchand, B.Sc.Tech.
Bordewick, Olaf Unger, B.Sc.
Bregazzi, Percy.
Bullock, Percy Charles.
Butler, William Richard.
Carnegie, James.
Choa, Chin Som, B.Sc.(Eng.).
Clayton, Harry.
Clifford-Jones, Edward Thomas.
Cooper, Andrew Ramsden.
Cooper, Arthur.
Corkett, John Frederick L., B.Sc.(Eng.).
Crawford, Cecil George, M.Eng.
Davis, Horace Gilbert, B.Sc.(Eng.).
Dennis, Nigel Henry.
Dixon, Dermot Henry J. P., B.Eng.
Dowson, Christopher Henry.
Dransfield, Frank, B.Sc.(Eng.).
Eatwell, Henry Thomas.
Farrow, Reginald Henry M.
Fenton-Jones, Hugh.
Galea, Robert Fred.
Galloway, James.
Gibbs, William John, B.Sc.
Greenwood, Fred, B.Sc.Tech.
Gurney, John Leslie.
Hall, Harold John.
Hallawell, Austin Morris, B.Sc.(Eng.).
Hallett, Harold James.
Harber, Frank Ollerenshaw.
Harrison, Walter James.
Herbert, Robert Henry.
Hickleton, Charles John.
Holloway, Arthur Gordon P., B.Sc.
Holmes, Sydney Jackson.
Howe, Alfred Henry.
Howell, Eric Ernest, B.Sc.
Hughes, Edward Llewelyn.

Student to Graduate—continued.

Humm, Robert William.
Irving, Leslie John.
Jackson, Frederick Samuel.
Jago, Ronald Albert.
Jones, Leslie Newton.
Jones, William Handel.
Kelso, Alexander.
Kemp, Robert James A.
Kilner, William Norman.
Langford, Stanley, B.Eng.
Leben, Henry, B.Sc.(Eng.).
Ledward, Thomas Archibald.
Lennie, George, B.Sc.
Lupton, Tom Reginald, M.Sc.Tech.
MacMillan, Archibald.
Macnaughton, Arnold Ingram, B.Sc.(Eng.).
Maddocks, William Arthur.
Mellor, Clarence Hedley.
Milne, Alexander James.
Moore, Douglas.
Mooney, Allan McLeod.
Morgan, Arthur Edward K.
Morton, Charles Albert, B.Sc.(Eng.).
Moussa, Mohamed.
Munro, James Alexander.
Newman, Samuel Emil.
Ockerse, Roebert Gerrit.
Overington, Lionel Eric.
Owen, John Ewart.
Paley, Frederick Raymond.
Parsons, Daniel Blundell, M.Eng.
Partridge, Douglas Grenville B., B.Sc.
Paton, Allan Park, B.Sc.
Payne, Eric Arthur.
Pearce, Cecil.
Phillips, Alexander Stevenson.
Phillips, Charles George R.
Phillips, Edmund Arthur.
Pimble, Cyril Charles.
Plowman, Mark Frederick R.
Plummer, Reginald.
Porter, Alfred Gordon.
Pye, Cecil Norman, M.Eng.
Ratcliffe, Thomas, M.Sc.Tech.
Richardson, Richard Paul.
Rogers, Robert Arnold, B.Sc.(Eng.).
Roy, Kamala Prasanna, B.Sc.
Sabikhi, Nihal Chand.
Sadler, Cyril William C.
Sakr, Hussein Tewfik.
Samples, Walter, B.Eng.
Scroggie, Marcus Graham, B.Sc.
Seagrave, Harry George.
Short, William James C.
Singh, Lochan, B.Sc.(Eng.).
Slack, Alvan Esmond, B.Sc.Tech.
Smith, Dorothy (Miss).
Smith, William Francis, B.Sc.
Sowter, George Alfred V., B.Sc.(Eng.).
Stanley, John Frank, B.Sc.(Eng.).
Stevens, Frank Gladstone.
Stirling, Wallace, B.Sc.
Street, Raymond Walter.
Sutherland, Robert Alexander, B.Sc.(Eng.).
Thomas, Horace Augustus, M.Sc.
Thompson, Edgar.
Underwood, Gilbert Vivian.
Vedanthiengar, Komandur.
Voelcker, John Westgarth, B.Sc.
Walmsley, William Herbert G., B.Sc.Tech.
Watkin, Harold.
Wells, Brian Lewis, B.Sc.(Eng.).
Weston, George Edward D.
White, Edward Paul.
White, Edwin James.
Wilman, William Eric.
Winder, Reuben Frederick.
Wright, Maurice McGill.
Wrightson, Francis Baliol, B.Sc.
Zula-Crosse, Frederick Cecil, B.Sc.

The President: The Council have decided that the fifth award of the Faraday Medal shall be made to Colonel R. E. Crompton. The Medal is awarded for notable scientific or industrial achievement in electrical engineering, or for conspicuous service rendered to the advancement of electrical science, and I think it will

be agreed that Colonel Crompton's work comes under both these heads.

A paper by Messrs. J. Lindley Thompson, M.Sc., Member, and H. Walmsley, entitled "Notes on the Testing of Static Transformers" (see page 505), was read and discussed. On the motion of the President a hearty vote of thanks was accorded to the authors, and the meeting terminated at 8.10 p.m.

51st MEETING OF THE WIRELESS SECTION, 3 FEBRUARY, 1926.

Major B. Binyon, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section, held on the 6th January, 1926, were taken as read and were confirmed and signed.

A paper by Mr. J. Hollingworth, M.A., B.Sc., Associate Member, entitled "The Propagation of Radio Waves" (see page 579), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.40 p.m.

738th ORDINARY MEETING, 4 FEBRUARY, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 21st January, 1926, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 278) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Mr. E. V. Clark, B.Sc., Associate Member, entitled "Power Factor and Tariff" (see page 625), and a paper by Mr. E. W. Dorey, Associate Member, entitled "The Improvement of Power Factor" (see page 633), were read (the former, in the absence of the author, by Mr. E. L. Hill) and discussed.

On the motion of the President votes of thanks to the authors, and to Mr. Hill for reading Mr. Clark's paper, were carried with acclamation, and the meeting terminated at 7.40 p.m.

INSTITUTION NOTES.

Nomination for Election to the Council.

In addition to those members nominated by the Council (see page 717) the following member has been nominated for ballot as Ordinary Member of Council:

R. F. FERGUSON (*Nominated by* Messrs. J. H. Bowden, J. Christie, J. E. Edgecombe, S. E. Fedden, H. Marryat, R. B. Mitchell, E. S. New, A. M. Sillar, W. C. P. Tapper and E. J. Williams).

Associate Membership Examination Results: April 1926.

Passed.

Aldis, R. F. (Windsor).
Anslow, C. L. (London).
Azimuddin, M. (Bristol).
Ball, R. D. (London).
Birtwistle, M. (Enfield).
Bishop, J. L. (Southampton).
Bland, J. G. (Northampton).
Booth, W. L. (Birmingham).
Brown, Harry (Edgware).
Burton, W. C. L. (London).
Butterley, A. D. (Sacriston).
Cansdale, J. H. (Brentwood).
Child, I. H. (London).
Colburn, F. (London).
Cooper, W. V. (Bolton).
Crowson, G. A. (High Wycombe).
Davidson, H. S. (Wolverhampton).
Davies, E. C. (Birmingham).
Dodman, E. J. (Stowmarket).
Elford, E. N. (Cobham).
Ely, E. S. (Stafford).
Ely, R. E. V. (Sutton).
Fielder, C. R. (London).
Galea, R. F. (Malta).
Goodwin, R. (Derby).
Gower, S. C. (Hull).
Gray, G. W. E. (Grimsby).
Greenup, L. S. (South Shields).
Greenwood, L. (Birmingham).
Griffin, R. M. J. (Leatherhead).
Hall, W. S. H. (Derby).
Hart, A. (Manchester).
Hawkins, E. J. (Braintree).
Holt, W. R. K. (Margate).
Hopkins, B. G. (Rugby).
Hopkins, H. R. (Manchester).
Hoskin, F. (Plymouth).
James, D. J. (London).
Jones, G. L. R. (Bletchley).
Kenyon, J. (Blackpool).
Kerr, D. R. (Gloucester).
Kim, G. C. (Preston).
King, R. (Norwich).
Kitching, P. H. (Sanderstead).
Lardner, E. (Birmingham).
Litherland, E. (Doncaster).
McCormac, A. (Leeds).
Maloney, S. J. (London).
Mather, F. (Manchester).
Milner, D. R. F. (Derby).
Murrell, A. C. (Birmingham).
Myers, F. H. E. (Southsea).
Nadarasa, A. (London).
Nicoll, H. W. (London).
Nunn, C. (Crewe).
O'Dell, H. J. S. (Southsea).
Osborn, L. G. (Hebburn).
Pheasant, J. W. A. (Grimsby).
Pimble, C. C. (Stoke-on-Trent).
Priestley, F. (Devonport).
Rhys-Jones, J. E. (London).
Robey, L. J. (Leigh-on-Sea).
Sammons, G. H. (Wolverhampton).
Scott, A. T. (Watford).
Smith, F. W. (Birmingham).

Passed—continued.

Smith, L. M. (London).
Smithells, T. A. (Manchester).
Stonehouse, M. D. (Wolverhampton).
Taylor, J. (Darwen).
Thompson, C. B. (London).
Treloar, N. G. (Stockport).
Tyacke, N. A. (Chichester).
Vincent, S. C. (Nottingham).
Waddecar, A. (Manchester).
Walsh, S. F. (London).
Watson, E. P. (London).
Wells, J. S. (Birmingham).
White, W. G. (Brighton).
Williams, J. R. (Lewes).
Wills, W. H. (Worcester).
Woodward, E. E. (Darlington).
Wyatt, C. B. (Manchester).

Passed Part I only.

Lower, J. H. (Gillingham).
Marshall, G. N. (London).
Mellor, C. H. (London).
Orme, J. L. (Cardiff).
Paul, S. W. (Southampton).
Philpott, S. F. (Birmingham).
Shears, H. H. (Bournemouth).
Snoxell, R. E. W. (Bedford).
Telemat, S. M. (London).

Passed Part II only.

Addenbrooke, J. H. (Wolverhampton).
Bristow, R. E. (London).
Coulehan, J. C. (Hull).
Gravett, R. M. (Wolverhampton).
Green, H. (Ilkley).
Holland, A. E. (Hull).
McManus, J. (Halifax).
Marshall, L. B. (Walsall).
Metcalfe, S. (Sutton).
Munn, H. S. (Birmingham).
Prangnell, F. N. (Newcastle-on-Tyne).
Smith, A. J. (London).
Symes, G. L. (Southsea).
Tennison, A. J. (East Croydon).

Surrey Group Anti-Aircraft Searchlight Companies R.E. (T.A.).

The Secretary has been asked to publish the following information:—

There are vacancies for Commissioned Officers in the above unit, which has been recently formed and consists of three companies, having headquarters at Croydon, Kingston-upon-Thames and Guildford. The Croydon Company has an out-lying section at Redhill, and the Guildford Company will probably have sections at Farnham and Woking. The Group Headquarters are at Kingston-upon-Thames.

The Companies work chiefly with the Royal Air Force, and are equipped with 90 cm and 120 cm searchlight projectors, power for which is supplied from either stationary engine sets or from petrol-electric lorries. Sound-locating instruments are provided for directing searchlight beams on to the target by sound, or for following targets in unfavourable weather. Training is carried out in co-operation with the Air Defence

Squadrons, R.A.F., who provide machines to act as targets during drill hours. An annual camp is held, lasting for 15 days, and usually takes place at a health resort.

Technically qualified men are required as officers. Candidates must be of British nationality and possess one of the following qualifications :—

(*a*) Have served for 6 months in the Regular or Territorial Army and undertake to pass Certificate " A " O.T.C.

(*b*) Have served overseas with an Expeditionary Force or in the Royal Navy for 3 months and be recommended by a Commanding Officer under whom they have served.

(*c*) Have previous O.T.C. service and Certificate " A ".

Alternatively, a candidate with no previous service may undertake to qualify for Certificate " A " within 12 months of being commissioned.

An outfit allowance of £40 is granted on being commissioned, provided the candidate has not previously received any outfit allowance during the last 3 years. Full Army pay and allowances are paid while at camp or on courses, and travelling expenses to drills, etc., are refunded. Associate Members of the Institution of Electrical Engineers are eligible for the issue of Royal Engineer pay in addition.

Full information can be obtained from the Adjutant, Surrey Group A.A. S/L Cos. R.E., 145, London Road, Kingston-upon-Thames.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 May–25 June, 1926 :—

	£	s.	d.
Aitken, I. M. E. (Manchester)		2	6
Allward, M. J. (London)		5	0
Andrews, W. F. (London)		10	0
Atkins, J. W. (London)		5	0
Aylott, H. J. (Chelmsford)		10	6*
Baggaley, C. F. (Mansfield)		5	0
Bannister, H. (Leeds)		5	0
Barclay, W. R. (Birmingham)		5	0*
Barnes, C. W. (London)		5	0
Beale, H. R. (Lower Hutt, N.Z.)		8	6
Beck, J. W. (Ilford)		5	0
Beckwith, F. (Rugby)		2	6
Beer, W. E. (Teddington)		3	6
Brown, R. C. (Preston)		5	0
Burgess, A. B. (Glasgow)		3	6
Cape, A. B. (Birmingham)		2	6*
Chamberlain, R. H. (Northampton)		2	6*
China Local Centre	10	10	0*
Clinch, W. N. C. (Enfield)		10	0
Coates, W. A. (Tokio)	1	0	0*
Coe, G. D. (Wrexham)		10	6
Colborn, C. H. (London)		8	6
Collins, A. (London)		5	0
Combes, F. R. (Auckland, N.Z.)		5	0*
Corkil, W. A. (Penang)		5	0
Coxon, J. (London)		5	0
Cribb, E. H. (Coventry)		2	6*
Cropley, C. P. (Burgess Hill)		8	6
Davie, J. F. (London)		10	6
Downing, H. E. (Birmingham)		2	6
Duckworth, L. S. (Bowden)		3	6*
Duncan, R. A. S. (Aldershot)		10	0
Earle, B. L. (Brighton)		15	0
Edgar, F. J. (London)		10	0
Electrical Engineers' Ball Committee	65	0	0
Elford, A. H. S. (Birmingham)		2	6*
Elliott, F. F. (London)		10	0
Elmhirst, R. J. (London)		5	0
England, C. J. (London)		5	0
Evans, P. (Stafford)		10	6
Everest, A. R. (Rugby)		10	6*
Eynon, W. (London)		5	0*
Faulkner, H. (Rugby)		2	6
Field, H. (Swansea)		2	6
Ford, C. R. (London)		5	0
Fowler, C. F. (Leeds)		2	6
Fowler, W. E. (London)		5	0
Frampton, H. G. (Manchester)		5	0
Frankling, A. E. (London)		5	0
Frazer, W. A. (Belfast)		5	0
Garland, J. (Concordia, Cape)		15	0
Gerrard, F. J. (London)		5	0
Gibbins, J. (Newcastle-on-Tyne)		5	0
Glen, J. B. (North Shields)		5	0
Gothard, W. B. (Llandudno)		5	0
Greenhalgh, E. (London)		10	6
Griffin, J. G. (St. Albans)		10	0
Hammond, G. W. (Leeds)		3	6
Hebditch, E. G. (Singapore)		3	6
Hobson, R. S. (Loughborough)		5	0
Hodson, D. A. P. (Saffron Walden)		2	6
Hogbin, A. (Kingston-upon-Thames)		3	6
Howell, A. H. L. (Haverfordwest)		5	0
Humphreys, H. F. (Stoke-on-Trent)		5	0
Hunter, E. I. (Manchester)		3	6
Jack, H. (Rugby)	2	2	0
Jakeman, R. G. (Birmingham)		5	0*
Jewell, C. J. (Norwich)		15	0
Jewson, F. K. (London)		5	0
Keating, A. E. (London)		5	0
Kelsall, H. A. (Chandernagore, Bengal)		10	0
Kempster, J. W. (Glasgow)	1	1	0
King, C. D. (London)		5	0
King, W. H. (Otira, N.Z.)		5	0
Klitz, R. W. (Wrexham)		10	0
Langton, J. L. (Manchester)		10	0
Laurence, A. H. (Sowerby Bridge)		5	0
Lawson, F. A. (London)		5	0
Leeves, A. H. (Old Colwyn)		5	0*
Lewis, T. E. (Cardiff)		5	0
Lindley, G. (Barnsley)		8	6
Love, E. G. (London)		5	0
Lowe, W. (Birmingham)		5	0
Main, F. W. (London)		10	0*
Manly, E. H. (Sutton, Surrey)		5	0

* Annual Subscriptions.

* Annual Subscriptions.

	£	s.	d.
Mather, J. (Stockton)		10	0
Mather, J. F. (Bradford)		5	0
Mitchell, G. W. (Hull)		2	6
Mittell, B. E. G. (Iver, Bucks.)		10	0
Murray, G. (Hong-Kong)	2	2	0
Naftel, P. H. (Birkenhead)		15	0
Needes, E. C. (Pontypridd)		5	0*
Niven, A. M. (Edinburgh)		10	0
Perrin, C. M. (Shanghai)	3	0	0
Pike, F. A. (London)		5	0
Powell, E. B. (London)		5	0
Pratt, L. H. (Newcastle-on-Tyne)		5	0
Priest, C. W. A. (London)		5	0
Ross, D. B. (Glasgow)		5	0
Sabine, H. W. T. C. (Chester)		10	0
Samuel, H. P. (West Bromwich)		5	0
Scottish Centre Entertainment Fund	15	0	0
Seaman, A. G. (London)		10	0
Sheldon, R. A. (Birmingham)		5	0*
Shipley, J. F. (Kew)	2	2	0*
Sillar, L. G. (Calcutta)		8	6

* Annual Subscriptions.

	£	s.	d.
Simpson, A. A. (Birmingham)		2	6*
Skoulding, J. H. (Brentford)		1	6
Slorach, J. W. (Hamilton, N.B.)		5	0
Steel, H. G. (Tynemouth)		5	0
Stewart, A. (Teddington)	1	1	0
Stobbs, J. G. (Middlesbrough)		2	6
Taylor, H. W. (Stroud)		5	0
Thomas, T. B. (Aberdare)		3	6
Timmis, A. C. (Beaconsfield)		5	0
Trees, T. D. (London)		5	0
Unwin, D. J. (Colombo)		5	0
Upton, R. H. (Wallasey)		3	6
Upward, C. F. (London)		15	0
Wadsworth, T. H. (Rainhill)		5	0
Watson, C. G. (Alston)	1	5	0
Wheeler, O. (Bristol)		5	0
Williams, A. (Manchester)		15	0
Williams, J. W. (Wrexham)		5	0
Wilson, A. S. (Liverpool)		10	6
Woodward, E. E. M. (London)		10	0
Young, J. (Birmingham)		5	0*

* Annual Subscriptions.

ELECTRO-FARMING, OR THE APPLICATIONS OF ELECTRICITY TO AGRICULTURE.

By R. Borlase Matthews, Member.

(*Paper first received* 20*th November*, 1925, *and in final form* 29*th January*, 1926; *read before* The Institution 4*th March*, *before the* North-Eastern Centre 9*th March*, *before the* South Midland Centre 10*th March*, *before the* North-Western Centre 30*th March*, *and before the* Western Centre 12*th April*, 1926.)

Summary.

The paper deals with the progress made since a previous one on the same subject. It is also a sequel to the report of the I.E.E. Committee on Electricity in Agriculture.

The field covered by electro-farming is now so wide that the paper has been confined to the latest developments and the chief points about which information is at present required. These are classified under three headings:—

"The Rural Distribution System" draws attention to the importance of dealing with statistics on the basis of the route miles and not the area supplied. It is claimed that where a quarter of the area is arable land, the supply is profitable.

"The Farm Installation and its Uses" deals with the practical points which arise in planning a farm installation, including the special requirements of electric motors for farms. Reference is made to new methods of speed reduction and to a plan for improving the load factor by restrictive control of the larger apparatus. The latest developments are discussed, such as intensive illumination for stimulating plant growth, and the possibilities of increasing the yield of honey.

The last heading covers some of the aspects of "Work on the Land, and Haulage." The most important feature is electric ploughing, which ensures a profitable load for the supply undertaking. A specification is given of the author's ideal of an electric tractor suitable for the smaller farm. It is designed for ploughing as well as all other field operations and general haulage, and is fitted with a half creeper track and also a storage battery. The object of the latter is to enable the tractor to proceed from field to field and also to haul loads on the public roads. When carrying out field work it is intended that the machine should take its supply from overhead lines by means of a cable laid on the ground. Mention is made of a method for reducing plough friction by making the plough coulter alive. Other matters dealt with are: rotary tillers, progress in making hay without sunshine, new developments in electro-silage, and a central method for liquid-manure distribution over farm lands. In an Appendix, a bibliography of the more important references to the subject is provided.

Generally, the paper sums up the results of a great deal of full-scale experimental work carried out by the author.

Table of Contents.

Since the author presented to this Institution his previous paper on Electro-Farming,* very considerable progress has been made.

An outstanding feature of the past year is the report of the I.E.E. Committee on Electricity in Agriculture,† which coincided with the Report presented by Mr. C. Dampier Whetham, on behalf of the Research Committee to the Royal Agricultural Society of England.‡

Periodical conferences are now held in most countries. A beginning was made in Great Britain (at the Chester R.A.S.E. Show, 1925) due to the enterprise of the British Electrical Development Association. This is to be followed by a second meeting at the R.A.S.E. Show in July 1926, at Reading. Further, the new development now has its own journal—*Electro-Farming*.

It is strange that one of the most backward countries in this development is the United States of America. Out of 15 788 million h.p.-hours per annum used on American farms, only 850 million are supplied electrically. However, it seems likely that they will soon be in the van, for the matter is at present being taken up most energetically and large sums of money are being expended upon full-scale experimental work.

* *Journal I.E.E.*, 1922, vol. 60, p. 725.
† *Ibid.*, 1925, vol. 63, p. 838.
‡ *Journal of the Royal Agricultural Society of England*, 1924, vol. 85, p. 246.

The subject has now become so wide in scope that the author proposes to deal only with some of the more recent developments and, in particular, with those matters which are at present of most interest. The general problem may be classified under the following main headings :—

(i) The rural distribution system.
(ii) The farm installation and its uses.
(iii) Work on the land and haulage.

(1) The Rural Distribution System.

Route length as the basis of rural distribution.—In quoting statistics concerning urban central-station distribution, the load density is often stated in terms of annual consumption in kilowatt-hours per square mile. The same method is therefore apt to be applied to rural districts. Even in the towns the facts are much better represented by considering cable route-miles instead of square miles of supply area ; in the country this applies still more, since normally the rural population is located chiefly beside the old-established trade routes, the easy roads through the valleys and through the centres of rich arable land.

Table 1.

Units and revenue per mile of route.

	kWh per annum		Annual receipts per mile
	per mile	per km	
Rural— Lighting, cooking, heating and barn work on farms	10 500 to 22 500	6 250 to 10 400	£175 to £375
Ditto, plus ploughing ..	34 500 to 48 000	21 600 to 30 000	£430 to £600
Rural industries and lighting	4 000 to 8 000	2 500 to 5 000	£50 to £100
Totals	38 500 to 56 000	24 100 to 35 000	£480 to £700
Urban— 100 consumers per mile ..	20 000	12 500	£250 to £333

Remunerative rural areas.—Table 1 gives some comparisons of units consumed and probable income for rural and urban conditions, in terms of miles (or kilometres) of route.

There are already routes where the consumption per mile of 10 000-volt distributor without ploughing is equal to or exceeds the urban figure in Table 1.

It will be seen that the possible revenue per route mile of rural line is at least as large as that from the usual town load known to be profitably supplied. It must be remembered that villages and rural industries will take a considerable supply in addition to that consumed by the farms. Anything over 5 000 units per annum per mile is profitable. The important matter is to exercise economy in construction work. Interest and depreciation for a rural line are, of course, much lower than for an underground distributor in a city. Again, the capacity of an overhead line can be cheaply increased in the future, the only expense being for conductors, insulators and labour for erection.

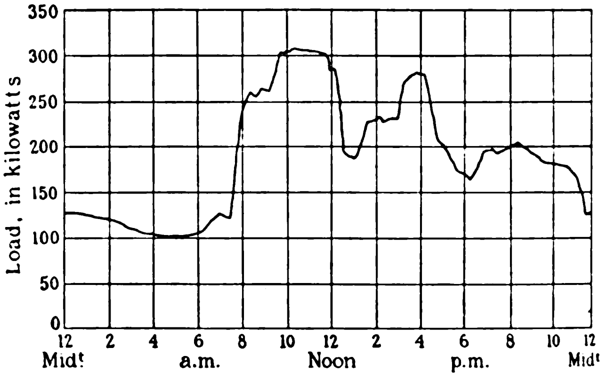

Fig. 1.—Typical load curve for an English rural distribution line.

Practical experience indicates, at the present stage, that in order to provide a remunerative electricity supply a quarter to a third of the area must be arable or rich dairy land. The point is not so much whether electric ploughing is to be employed or not—it will probably not be used in many districts for a few years—as the fact that a farmer with a good proportion of arable land needs to treat, in some way, the crops which he produces, or else he has to prepare food for stock. The amount of power necessary for these purposes has a direct relation to the area of land under the plough, and also to the fertility of the soil. In some of the more fertile parts of Europe the consumption of electricity is already 100 units per acre, without taking into account any current actually employed on the land for ploughing or other purposes. Ploughing and cultivation would have consumed an additional 60 units per acre, while treatment and handling of the crops would absorb up to 40 units per acre. Over and above all this, there is a very important load that has not yet been touched, viz. that of haulage, estimated at about 75 units per acre. Thus, under ideal conditions, it is possible to conceive a consumption of 275 units per acre, based upon present practice. As an illustration of what that would mean to this country alone, assuming that its 57 million acres of land were all suitable for agriculture, on the above basis of consumption the requirements would be about 16 000 million units per annum, whereas the present output of all the central stations in the country, including the output for railway work, is only 7 415 millions. Thus the

hypothetical requirements for agriculture would be more than twice those for all other purposes. If the agricultural consumption were only one-twentieth of this, it would be as great a load as that of the power companies on the North-East coast of England, admittedly a very large output (about 800 million units per annum).

These approximations are supported by a statement made by the United States Department of Agriculture (which has recently made a very careful survey of the consumption of all kinds of power used on farms)—"agriculture in the United States uses practically as much primary power as all manufacturing and central-station plants combined." This seems to be the position in almost any country.

Without ploughing or haulage, a figure of 10 to 30 units per acre may at present be taken as a fair average upon which to base calculations for this country. Ploughing and cultivation would take 45 to 60 units per acre, while thrashing would need 24 to 45 units per acre, depending upon the heaviness of the crop. The demand of rural industries usually amounts to 25 to 30 per cent of the purely agricultural consumption. As more industries are attracted to the country, this proportion increases. An analysis of the electricity supply to 34 rural districts in Germany showed the results set out in Table 2, and these could be very considerably improved if the farmers were shown how to make better use of the supply.

TABLE 2.

Consumption of electrical energy in 34 German rural districts (without electric ploughing).

	kWh per acre	kWh per hectare
Lighting	12·5 to 22·5	30 to 55
Power	27·5 to 42	65 to 100
Totals ..	40 to 64·5	95 to 155
Average	50	125

At the first meeting of the Electro-Farming Section of the World Power Conference held in London in 1924, the author read a paper upon "Electro-Farming Economics." * The most interesting fact elicited from the discussion was the confirmation from several countries that, if properly laid out, a rural electrical distribution scheme is profitable. The author was discussing this all-important matter recently with a prominent director of successful French electricity-supply companies. He stated that the usual definition of a rural area was—one in which it would not pay to supply electricity, based on the existing demand for power. After the lines were installed, according to his experience, so many small auxiliary industries started up in conjunction with the farm loads, that it paid the supply undertaking. The district then ceased, however, to be a rural area in the sense of the above definition.

* Paper No. 266: "First World Power Conference," London, 1924.

Extra-high-tension layout.—The layout of the line only differs from the usual practice in that additional tappings have to be provided *en route*. Normally, an extra-high-tension transmission line merely serves to link up the super-power stations in two or more important cities or towns, tapping through substations. Under conditions of rural distribution these substations will be at more frequent intervals and probably of the open-air type (and thus cheaper). It has long been customary to duplicate extra-high-tension lines, and advantage may be taken of this fact in new layouts destined to provide for any intervening rural demand. Actually it will often be found advisable to utilize two (or even three) distinct routes at some considerable distance apart. One route might be the most direct between the towns. The second (and third, if required) should go through the centres of gravity of the anticipated rural demand. In other words, what is normally an auxiliary service for the city will become the main supply for the intervening area. At the same time, it is available to render assistance to that city in case of emergency.

Distribution system.—The layout is affected by the low-tension voltage required. In the initial days of rural supply, in order to reduce line construction costs, it will undoubtedly be the practice to work with a greater voltage-drop during the day-time than would be permissible for city work.

On the Continent, low-tension supply seems to be settling down to 380 volts, three-phase, 50 cycles, for power, with 220 volts between one phase and neutral for lighting; whilst in Great Britain favour is given to 400 volts, three-phase, 50 cycles, with 230 volts for lighting. The possibilities of single-phase rural distribution and the use of galvanized steel conductors are receiving very considerable attention, but so far the methods are not utilized to any great extent. In any case the provision for the supply of heavy loads, such as ploughing and thrashing, must not be overlooked.

To maintain the above-mentioned voltages, the countryside has to be set out in circular adjoining areas of approximately 3 miles (5 km) diameter, each supplied from a 10 000-volt sub-distribution system, connected to the main extra-high-tension distribution of 30 to 220 kV. At present a 25- to 50-kVA transformer is usually sufficient for each of these substations, but the transformer capacities will have to be increased later on.

In most countries there is an average of $1\frac{1}{2}$ farms and 2 other consumers per mile (1·6 km) of low-tension distributor. Each 10 000-volt transformer station will supply about 22 farms and 30 to 40 other consumers, including motors totalling up to 300 h.p. Though the load factor per motor is low, that per farm (the more important matter) is high, based on its maximum demand. It averages at present 35 per cent, giving a consumption of 90 000 units per annum, i.e. 43 000 units per route mile of 10 000-volt distributor.

An example of extra-high-tension distribution.—Assume two super-power stations, "G" and "C," situated 50 miles (80 km) apart (see Fig. 2) and connected by a 110 000-volt line. If the district were arable there would be an area of supply of about 2 000 square miles

(1¼ million hectares). On the basis of estimates made for city conditions, it would seem almost hopeless to think of attempting to supply such an area. However, if the work is carried out on the lines suggested in this paper, basing the distribution on the route length, it will be found that an annual consumption of 96 million kWh can be supplied by increasing the length of extra-high-tension line from 50 miles (80 km) to 200 miles (320 km). In addition, there would have to be provided five open-air substations and 375 miles (600 km) of 33 000-volt sub-transmission lines; and 500 miles (800 km) of 10 000-volt feeders to the local low-tension substations would also be needed.

For the scheme set out in Fig. 2, one extra-high-tension line would go by the shortest route between the cities and two others would also be provided. Of these, one would run parallel on one side at an average distance of, say, 15 miles (24 km), and the other a similar distance away on the other side. Thus the five 110 000/33 000-volt substations may be situated at the centres of gravity of the local demands. In practice, the theoretical diagram (Fig. 2) would, of course, require considerable modification, though the routes suggested for the three extra-high-tension lines will be found to be characteristic. On approaching the towns, the density of the population and the demand for an electricity supply will increase. Also the distribution of the arable land will not be uniform. This may necessitate a modification of the position of the sub-stations.

It is assumed that the low-tension distribution net-

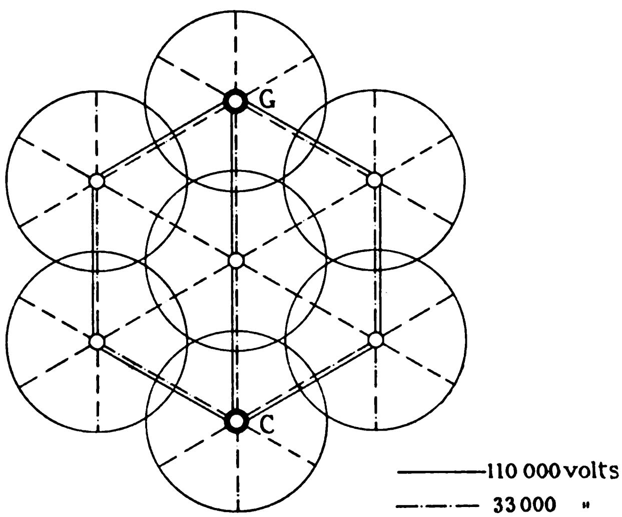

FIG. 2.—An example of extra-high-tension rural distribution between two generating stations "G" and "C," 50 miles (80 km) apart. The sides of the triangles represent distances of 25 miles (40 km).

work (380/220 or 400/230 volts) will be supplied by the local communities. Hence the power supply undertaking would have to consider only the costs up to and including the 10 000-volt substations.

Such a layout only requires one mile of extra-high-tension 110 000-volt line per 30 square miles (19 200 acres) of land (or 1 km of line per 5 000 hectares), plus a mile of 33 000-volt line per 8 square miles (5 120 acres) of country (or 1 km of line per 1 030 hectares), plus a mile of 10 000-volt line per 6 square miles (3 840 acres) of ground (or 1 km of line per 1 000 hectares). Ample provision of 33 000-volt lines is suggested, with a view to the supply of the ploughing and thrashing loads.

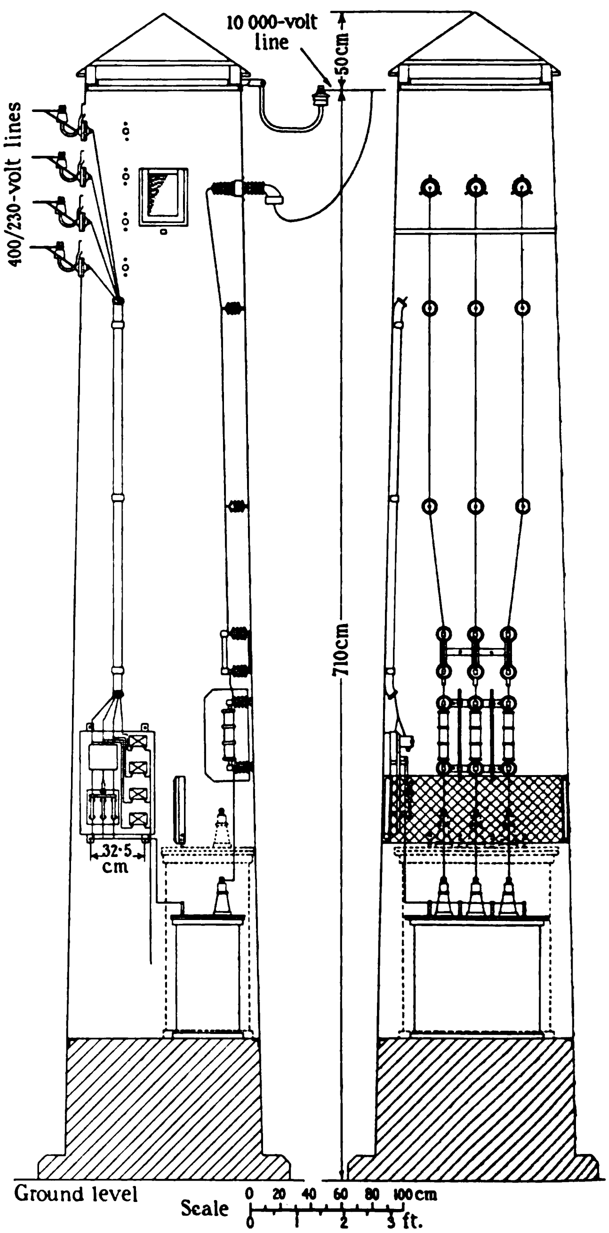

FIG. 3.—Transformer tower, with floor-level convenient for unloading the transformer direct from a vehicle.

Though the layout is hypothetical, it is based upon actual practice.

It is assumed that the economic range of a 10 000-volt line over a distance of 12 miles (19 km) is 250 to 650 kVA. Also that 33 000 volts is an economic voltage for transmissions of 25 miles (40 km) for quantities of power in excess of 800 kVA.

Details that reduce the cost of overhead lines.—The rural line is similar in costs and construction to the lines required for any other purpose. The matter that requires careful watching is so to design the line that most of the construction work on the poles, insulators, etc., can be done in the factory and not on the road side, where labour is so much more costly. Further, poles of a circular or polyhedral cross-section are to be preferred, since much time is saved if the poles have not to be aligned to match the lie of the conductors. Insulators and their cross-arms should be so designed that they can be clamped on the pole tops without any special drilling or similar work.

The high cost of tapping of the extra-high-tension lines at intermediate points is perhaps the greatest difficulty. It is receiving considerable attention at the moment. Undoubtedly the best plan is to provide a

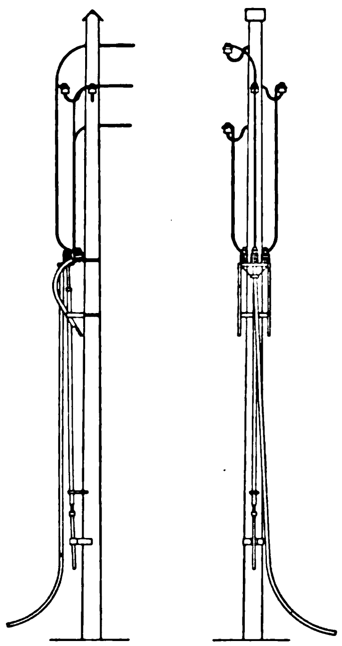

FIG. 4.—3 300-volt A.S.E.A. pole contact for portable farm transformers.

sub-transmission line at, say, 33 000 volts, connected at both ends to the extra-high-tension lines, giving in effect a ring main. From this, 10 000-volt feeders can be supplied for the 50-kVA substations at 3-mile (5 km) intervals along the rural routes. One advantage of this 33 000-volt sub-transmission is that wood or ferro-concrete poles of a simple character can be employed. Further, it reduces the tapping points from the extra-high-tension lines themselves to a minimum. Very often it is advisable to employ intermediate distribution lines at 1 500 or 3 000 volts. Maintenance work is much cheaper if the rural substation transformers are mounted at the level of a lorry platform (see Fig. 3).

Temporary connections.—Heavy loads which move from farm to farm or field to field as the work is finished are probably better connected to the 33 000- or 10 000-volt lines than to the low-pressure distribution system. The switches, protective gear, meters, etc., would, of course, be contained in portable transformer wagons, as is the present practice.

On several parts of the Continent it is permissible to connect these temporary loads by hooks on to 33 000-volt lines. In theory this hardly seems a good method, but the plant is always in charge of a skilled man and in practice the method apparently works well. It has the advantage that any convenient point on the high-tension line can be tapped. However, it is probably wiser to provide, as is done in other districts, extra insulators and poles for temporary tappings.

Excellent foolproof temporary connections are now available for 1 500 to 3 000 volts and also 10 000 volts. These can easily be used by the more intelligent farm hands (see Fig. 4). Their use means a considerable saving in transformer iron-losses, the transformers being cut out of circuit when not required.

(2) THE FARM INSTALLATION AND ITS USES.

Number of farmers using electricity.—Whilst the use of electricity is still a novelty in this country, nearly a million farmers in other countries are employing it, so that a considerable amount of experience is available. To-day over 500 British farmers are utilizing it, and the number is fast increasing. Over 200 uses for electricity have already been found on farms.* The author has 67 on his own 600-acre farm at East Grinstead. Owing to this large number of uses, a farm with one electric motor and perhaps an electric cooker cannot be called electrified. At least a dozen uses are needed to justify this description. Supply undertakings must give advice in order that the supply may be profitable both to them and to the farmers. Farm electrification means much more than belting a standard industrial motor to the existing agricultural machines, and each case must be carefully considered on its merits.

Wiring system.—The standard of wiring for farm buildings is gradually being raised, as it is very important to eliminate the fire risk. Contrary to usual town practice, it is customary to run the conductors outside the buildings under the eaves of the roof. One reason is that the buildings are usually old; again, during much of the year the wiring would be inaccessible if run inside, stored crops occupying all the available space.

For the interior wiring of the buildings where livestock is kept, such as stables and cow-houses, it is important to use conductors which can withstand a steamy atmosphere, often impregnated with either uric acid or ammonia fumes. Bare overhead conductors mounted on porcelain insulators are often used. The switches are then also mounted overhead, being controlled by turn rods running down the walls to convenient positions, where they are supported by simple bearings. Lead-composition-covered cables often give a good deal of trouble through chemical action. Where steel conduit is employed it must be served with hemp or similar material, impregnated with an oily paint. The best insulated conductor for farm purposes, in

* A selection of these is given in a paper by the present author (*Journal I.E.E.*, 1922 vol. 60 p. 726).

the experience of the author, is that known as "Maconite." This well withstands stable fumes and high temperatures such as that of a dairy steam boiler. When used in the open air, however, exposure to the sunshine seems to dissolve out some of the gums in the composition.

It is useful to provide a number of outlets for hand lamps. To avoid accidents due to faulty designs the type of hand lamp to be used should be specified. In many parts of the Continent where alternating current is used, small transformers are employed to reduce the standard lighting voltage of 220 volts to 50, or even 25 volts, for use with the hand lamp. Outlets for electric motors should be of an interlocked type, in which a plug cannot be removed or inserted unless the socket is dead.

Agricultural-type electric motor design.—On the Continent of Europe there is now an agricultural type quite distinct from the industrial type. Since the war such a large proportion of the output (75 to 90 per cent) of electrical manufacturers' motor-shops has been of the agricultural type, that such motors are now often supplied for industrial work, to the advantage of the factory using them.

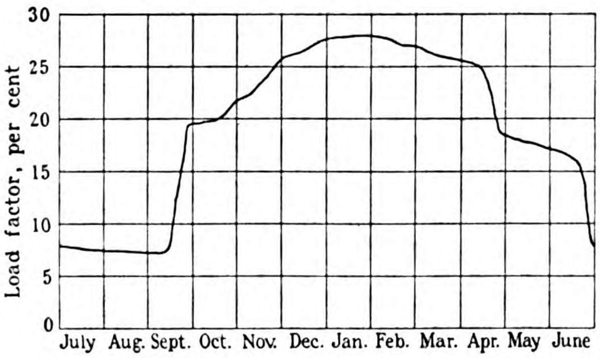

FIG. 5.—Load factor of a typical mixed dairy-farm.

The requirements are those of a mining motor, at the cost of an industrial one. The motor is expected to work in explosive and dusty atmospheres, to be left out in the rain, to have artificial-manure sacks placed on top of it, to be exposed to uric acid and ammonia fumes, and to receive practically no attention.

As lubrication is erratic, ball bearings should be used. A simple built-in overload circuit-breaker should be provided, and any starter should also be enclosed in the frame. The windings should be vacuum-impregnated so as to be moisture-proof. To keep down first cost an internal ventilation system is essential. To avoid special fixed wiring, a plug connection should be used for the cables. The motor must be capable of working in an inverted or vertical position. The outside should be smooth and easily cleaned.

Most of the motors can be started light, so that they can be of the squirrel-cage type. It is quite common to fit centrifugal clutches or sliding rotors to make starting still easier. Particularly in the larger sizes, wound-rotor motors with automatic short-circuiting and brush-lifting devices are useful, as they combine the advantages of both types.

Sizes of motors required.—A farmer starting to use electricity generally begins with one or two portable motors. After a few years, however, he finds it best to adopt what is now becoming the standard practice, and purchase motors to be permanently installed for individual drives.

The time saved through not having to re-adjust portable motors more than outweighs the extra interest and depreciation. Since each motor may be used for

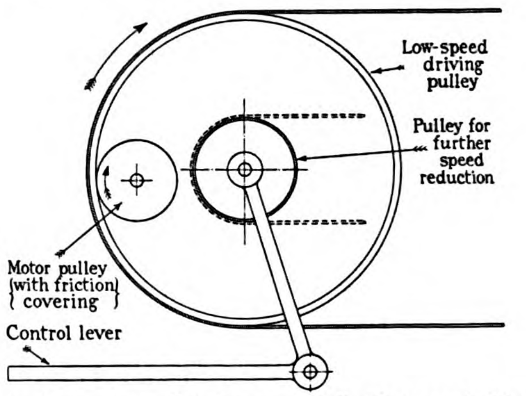

FIG. 6.—Internal friction drive controlled by cranked lever.

only a small portion of the year, it is unfair to base tariffs on the connected load, though the maximum demand may be taken into account. The farmer prefers a fixed charge plus a low rate per unit.

A 5 h.p. motor is the largest needed on most farms, except for ploughing, provided the supply engineer is in a position to recommend suitable farm machinery.

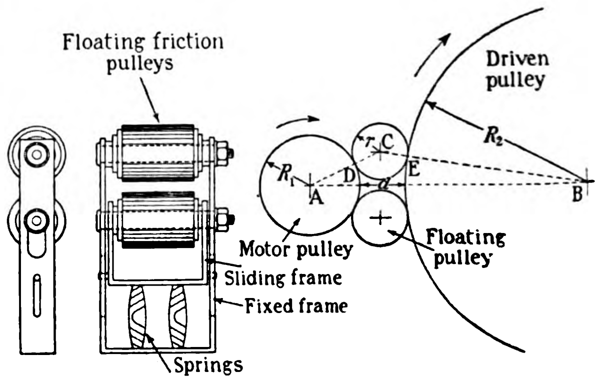

FIG. 7.—External friction drive with floating pulleys.

If this is the case, the power and load factors are much improved (see Fig. 5).

A 2 h.p. motor is useful in addition, with fractional h.p. machines for the lighter duties.

Improvement of power factor.—If the farmer cannot be persuaded to use small farm machines which can be operated by a 5 h.p. motor, he usually goes to the other extreme and uses very large ones, such as a thrashing machine combined with a straw presser, requiring a 25- to 40-h.p. motor. When such a motor is used on a much smaller load its power factor is very poor. To improve this, it may be fitted with a star-

delta switch for the stator, the star position being marked, say, " light load " and the delta position " heavy load."

As an example, a 25 h.p. motor when used for thrashing developed 24 h.p. For 10 hours a day on 120 days in the year it operated a dryer taking 13 h.p. Delta-connected, the power averaged 11·3 kW, star-connected it was 11 kW, thus saving 360 units per annum. More important still, the power factor was increased from 0·62 to 0·90. The same advantage was gained during 60 hours per annum in driving a grinding mill taking 10 kW and during 280 hours driving a chaff-cutter taking 9 kW.

are pressed together by a spring (see Fig. 7). A bracket forming a part of the machine to be driven holds the motor with its pulley at a definite distance from that of the machine. The portable friction-pulleys are sprung apart by hand and interposed between the motor pulley and the machine pulley. In this way a very convenient and compact speed reduction is obtained. Fig. 8 gives the proportions for the distance apart of the pulleys to give the best results.

Where a belt drive cannot be avoided, a device such as that shown in Fig. 9 is very useful. It gives a non-slipping drive with the pulley centres very close, the tight side may be at the top or bottom as desired, and

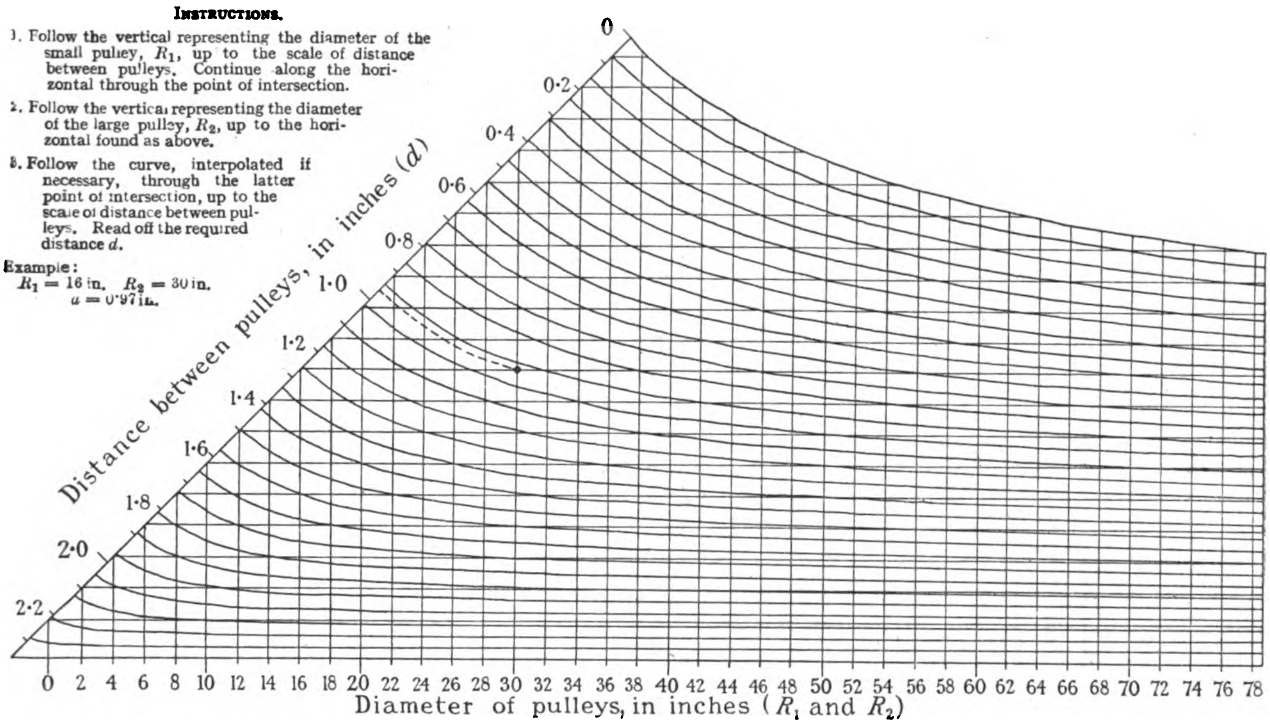

FIG. 8.—Abac for determination of distance between fixed pulleys for a tangential force of 60 lb., when using floating friction-pulleys.

Speed reduction for motors.—There are now a number of agricultural-type motors on the market, which by the use of self-contained compound-reduction gearing can be coupled direct to the machine to be driven.

This saves much time by avoiding belts, which in the hands of farm labourers unused to them give endless trouble.

For motors of 5 h.p. and under, friction drives can be used instead of gear wheels.

Diagrams are given of two examples of these. In the first case, the main reduction is done by an ingenious internal friction-pulley, the final drive being by belt (see Fig. 6). This method allows the motor to be started up without any load at all. By slowly bringing the friction-pulley in internal contact with the low-speed pulley, the load can gradually be put on. In the second case, two floating friction-pulleys are supported in a light portable frame, in which they

much smaller pulleys with a high-speed motor can be used.

Homestead equipment.—In the early stages the installation of electric power on farms has been greatly helped by the appeal to the housewife of electric lighting, electric cooking and electric washers. The apparatus supplied should be of the most robust and practical character. On some parts of the Continent to-day it is rare to find a farm without its electric washer, but it has cost one-fourth the price of the admittedly better type of washer available in this country. Whilst great improvements have been made in electric cookers of late, the designs have not yet reached the simplicity of the better-class gas cooker, though the schemes of hire and hire-purchase have helped towards this end.

Water-heaters are, of course, required in the kitchen and in the dairy. It is advantageous to couple these up

with an auxiliary fuel-fired heater. In connection with the latter, it has often occurred to the author that if a small pattern of direct-coupled electric blower were attached, it would assist the getting up of a fire.

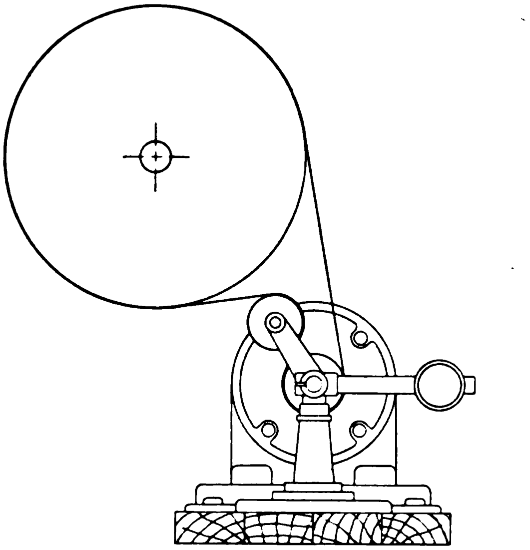

FIG. 9.—A typical counterweighted idler pulley, as often employed on the Continent.

employed 24 hours a day, the heat being stored up and utilized as required.

Economical control by multi-way switching.—It is wise to submit to the farmer suggestions that enable him to improve his load factor and thus purchase current on the most favourable terms, e.g. a method of multi-way switching, whereby, when the current is in use on one important piece of apparatus, other current-consuming devices cannot be switched on. In the farmhouse, the biggest loads are taken by (*a*) the electric oven, (*b*) the hot-plate of the cooker, (*c*) a water boiler, and (*d*) heaters for the rooms. As hot water is always useful, when other appliances are not in use the current can be switched on to the boiler, and so on, as indicated in Fig. 10. This diagram further suggests that, when the larger appliances are in use in the house, the motors in the farm buildings should be switched off. There is no practical objection to doing this, especially on the smaller farms, as it only requires a little rearrangement of the farm work.

Illumination of live-stock sheds and poultry-houses.—At least half-an-hour per day per man can be saved in the feeding of live stock by the aid of a good light.

Poultry-house lighting is now a recognized commercial practice, for the very good reason that there is an increase of 15 to 43 per cent in the egg production during the winter months, when prices are highest. This is clearly shown in Fig. 11. Contrary to the popular idea, the birds are not in any way strained by artificial lighting, as they get 10 hours' sleep each night. They are simply allowed ample time for feeding, as in the sub-tropical country where they

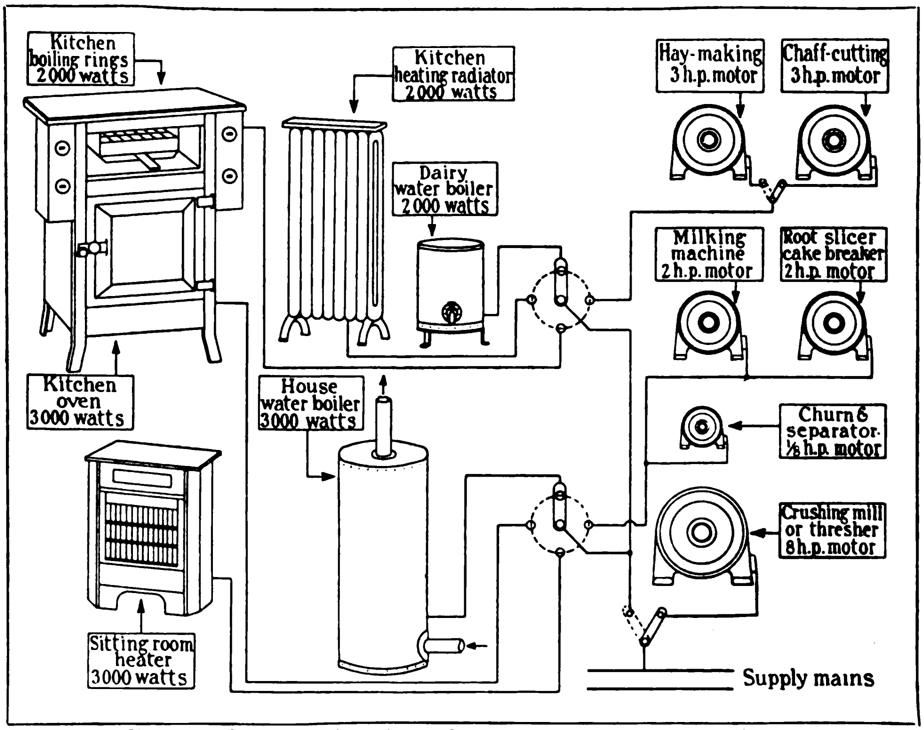

FIG. 10.—Diagram of a scheme for a 100 per cent farm load factor.
(The negative leads are omitted for simplification.)

Much work has been done of late in connection with heat-storage stoves, the heat being stored in water, cast-iron or soapstone. The object is the provision of a good load factor, as a small amount of current is

originated, instead of being partially starved owing to the long winter nights in this country.

Fig. 12 shows typical curves of poultry-farm maximum demand and load factor.

Intensive illumination to stimulate plant growth.—The author has recently obtained new results of commercial importance to the market gardener. The first is in connection with the transplanting of seedlings, and the second is one-night treatment of greenhouse plants to obtain more rapid progress. Ordinarily, when seedlings are pricked out, they are apt to fall down and become wilted by the next day. However, when electric light was applied during the night, the seedlings were fresh and vigorous on the next morning; in fact, they developed nearly a week's normal growth overnight. With six hours' light each night, daffodils flowered in four days and narcissi in seven days. In other words, the application of electric light had accomplished three or four weeks' growth in four to seven days. The illumination was much more intense than that previously tried, 1 000-watt gas-filled lamps and large enamelled parabolic reflectors being placed close above the plants.

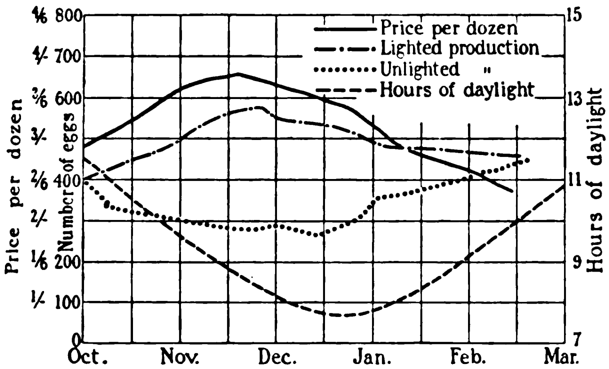

FIG. 11.—Gain in egg production due to electric lighting.

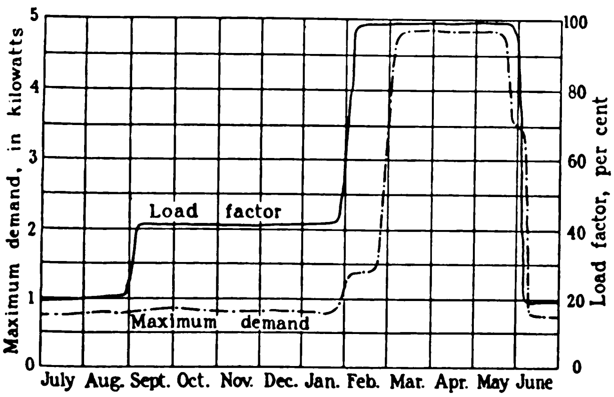

FIG. 12.—Load factor and maximum demand of a typical poultry farm.

Bees.—A novel application, which is still in the experimental stage at East Grinstead, is the artificial electric lighting and electric heating of bees in the early spring. The hives are all placed inside a house, instead of being kept in the open air in accordance with the usual practice in England. The basis of the idea is that, by this treatment, strong hives are obtainable at the time when the orchards are in bloom; thus about an additional 17 lb. of honey can be obtained per hive per annum.

Earth currents.—This, one of the earliest applications of electricity to agriculture, has lately been revived in a novel manner by M. Christofleau, in France. Confirmatory tests are at present being conducted in the author's garden. Further experimental work is, however, necessary to confirm the results obtained so far.

(3) WORK ON THE LAND AND HAULAGE.

From the point of view of the supply undertaking, the large available load, if work on the land is done electrically, means a certain amount of profit. So large a proportion of the power on a farm is used on the land, that it is also very important to the farmer himself. Hence all parties should consider very seriously the best methods of cultivation by electrical means.

Electric ploughing.—The advantages of electric ploughing are that practically unlimited power lies behind the plough, and that the cost per acre for electricity is very much lower than that for any fuel.

If electric ploughing is carried out on a large scale, the power required is so great that for an economical distribution system the voltage must be fairly high. This is a point overlooked in most discussions on rural electrification.

For motors which do not exceed about 40 h.p., 1 500- or 3 000-volt lines may be used. For larger motors the supply is usually taken from 10 000- or 33 000-volt lines. A portable transformer connected with the haulage set by a trailing cable is generally used. The motors are usually operated at 380 volts, three-phase, although one very successful equipment uses 5 000-volt motors. A meter is fitted on the low-tension side of the portable transformer. The high-tension connections are, as previously mentioned, often made by hooks where an electrician is in charge.

Most of the successful plants are of large size, capable of ploughing up to 27 acres a day (a team of horses can plough barely an acre a day). The capital cost is high. The area which can be ploughed in a season is that of a large number of average farms. For these reasons, such an equipment is only suitable for contractors or co-operative societies. Thus a difficulty in introducing it is the institution of the co-operative idea, particularly in a country where the farmers have an individualistic state of mind. Still, even in a country such as England, the steam plough has made very considerable progress in certain districts, such as Oxfordshire, Lincolnshire, and the Eastern Counties.

Ploughing is looked upon by the layman as a strictly seasonal occupation. It is, however, found in practice that an electric plough can be kept fully occupied for at least 200 days in the year, and this is quite a reasonable period over which to spread interest and depreciation. It is difficult to ascertain the costs of any form of mechanical ploughing, as the co-operative societies and companies, who generally carry it out, universally base their contract prices on the existing

horse-ploughing competition, also bearing in mind that at certain periods farmers are quite willing to pay a little above the horse rate if the work can be accomplished more quickly.

Small electric ploughs.—The demand for these is not yet very great, and they are still in an experimental stage. As the result of his investigations, the author has formed a clear idea of the most suitable type for the individual farmer.

It must be controllable by one man. It should be of the tractor type to obviate anchorages. The front wheels should have extra large pneumatic tyres. To prevent the formation of a hard pan below the surface of the ground, the pressure on the soil should be reduced to less than that due to a man's weight. This can be done by fitting in place of the rear wheels a creeper track, which may be of rubber and fabric, or rubber-tyred wheels may run on a metal track. Preferably the track should be capable of lying in a curve so as not to skid over the ground when turning a corner. On the tractor, two electric motors should be

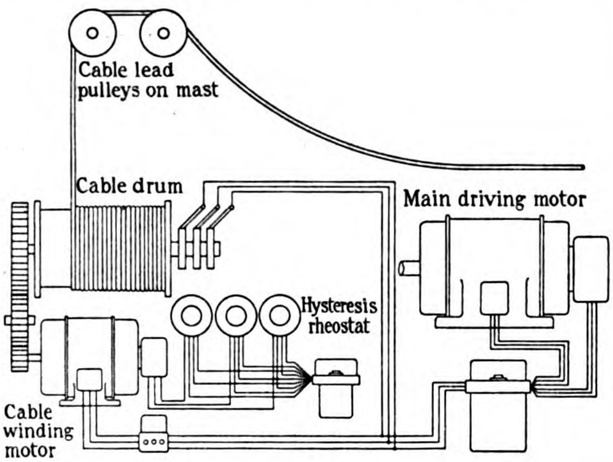

FIG. 13.—Hysteresis control for cable-winding motor of electric tractor.

fitted, one of about 25 h.p. for the main drive, and the other of about 2 h.p. for winding in the cable when it becomes slack. A derrick mast, supported on the chassis, should raise well above the ground the part of the cable nearest to the tractor. This mast should have a height of about 15 feet (4·5 m) and the cable should hang freely in the air for a distance of 35 to 45 yards (30 to 40 m); beyond this it can lie on the ground. In this way all risk of the tractor running over the cable is obviated, and the wear and tear on the cable is reduced to a minimum, since it has only to lie on, instead of being dragged over, the ground. The drum on such a tractor should hold 440 to 550 yards (400 to 500 m) of flexible cable.

A tractor of this type would plough an area of 40 to 60 acres (16 to 25 hectares) from a single contact in the middle of a field. In other words, continuous furrows of about ½ mile (800 m) in length could be ploughed. If a greater area is required to be ploughed from one contact point, it is, of course, quite easy to add another length of cable. It is, however, not often that areas of much more than 40 acres, and furrows more than ¼ mile long, are required to be ploughed at a time. Again, if a farm is equipped for electric ploughing, it is quite simple to arrange for several contact points. There are very few farms up to 500 acres which, if fitted with two distribution lines through the main axes of the land, could not be ploughed by a tractor of this type.

Fig. 13 illustrates a very ingenious hysteresis control for a cable-winding motor, which is successfully employed on the Continent. The cable-winding drum is operated by the motor through a friction drive. When the tractor is driven away from the source of supply, the cable is drawn out against the friction drive. On the other hand, when the tractor returns toward the original starting point, the cable is slackened. As the resistance to the motor drive is thus removed, the motor comes into operation and winds up the cable until it reaches a predetermined tautness. Owing to the hysteresis control, the operation of the motor is automatic; further, it will not burn out when the tractor stops or the cable drum reverses.

Major A. MacDowell has recently developed in Scotland an original form of single creeper tractor for ploughing, with which is incorporated a novel method of side-stepping the whole machine ready for the next furrow and also a new way of handling the flexible cable.

Transport.—One of the practical difficulties experienced in connection with electric ploughs is that of transport from field to field, and also the fact that they cannot be used for general haulage work on public roads. Large French tractors are equipped with petrol engines for transport purposes, which are also employed for emergency ploughing on land out of the reach of overhead lines. This expedient, however, adds very considerably to the capital cost of the equipment.

The author's proposal is to equip a creeper-tractor with storage batteries and thus employ it as an electric storage-battery vehicle for haulage on public roads, and also for haulage of timber and crops when it is not convenient to connect to an overhead line. Every farmer must have a vehicle which is capable of hauling between the farm and the nearest railway station or town, as well as for delivering loads to neighbours. A machine that can be universally employed is of considerable value to him, even if the speed is comparatively low on the public roads.

Many years ago accumulator tractors were experimented with for ploughing, but their weight was too great for practical work. Electric tractors fed by a trailing cable were also tried, but the cable lying on the ground directly behind the tractor was too easily overrun or damaged by being dragged over the ground. The advent of the creeper-track, however, coupled with the derrick support and automatic winding for the flexible cable, would eliminate these troubles. The possibilities of the four-wheel coupled drive must not, however, be overlooked.

Reference has been made to ploughing chiefly on account of the fact that it is the principal load on the farm. A tractor can also accomplish much other work,

such as cultivating, harrowing, rolling, seed drilling, harvesting, etc. All the existing farm implements except harvesting machinery can be used. With the latter, in the case of a tractor with a flexible cable, it is only possible at present to move it to and fro in a field instead of round the field. A standard harvesting machine can, however, be operated if the tractor is allowed to return light each time. It would be a very simple matter slightly to modify the standard reaper, so that instead of being a one-handed machine, it could be used on the right- or left-hand side as desired.

Reducing plough friction.—Quite a new development concerning the application of electricity to ploughing is to reduce the resistance of the soil to the ploughshare by passing a current of electricity between the coulter * and the ploughshare. An actual lubrication effect is secured by making use of a special property of soils to produce, by electrical means, a film of water between the furrow slice and the mould-board of the plough. The water in the soil seems to move from the positive electrode towards the negative. This property has, in fact, been used as a preliminary method of removing water from peat, preparatory to drying in the usual way. The idea is due to the work of E. M. Crowther and W. B. Haines, of Rothamsted Experimental Station, who have carried out a good deal of laboratory work in this connection, and eventually a full-scale series of tests at Greater Felcourt Farm, East Grinstead. Laboratory tests have shown that the friction under favourable conditions can be reduced by as much as one-third. These results have also been corroborated by Captain B. J. Owen in connection with mole draining.

Rotary tillers.—No less an authority that Sir John Russell has stated that it is impossible to say whether or not ploughing is actually an essential operation in farming. Though, so far, ploughing has been the accepted method of cultivating the soil, there are now a number of machines in existence which attack the problem in quite another way. These are known as rotary tillers. Just as the milling machine has largely superseded the planing and shaping machine in the engineering workshop, so it seems likely that the rotary tiller will have very many advantages. Certainly the action of ploughing seems very unmechanical in that really the ground is wedged over, which has a tendency to produce the very pan to which so many farmers object. Also the rotary tiller, as its name indicates, lends itself conveniently to an electric drive. Practical farmers condemned the earlier designs of these machines because they produced a fine tilth, which was apt to set down solidly after the first shower of rain. Now, however, improvements have been made in the construction of the tines or teeth, whereby both weeds and manure can be buried and the soil left in the form of clods, as is required by so many farmers. Hence, it seems probable that there will be a big future for this type of machine.

Crop treatment.—The most important matter under this head is thrashing. Owing to the steadier running of the electric motor, the output of good corn from an electrically-operated thrashing machine is increased by 5 per cent. Not a very large figure, but, as grain is comparatively valuable, it is one that is well worth while obtaining. Then there are many ways in which, by the aid of electricity, the farmer can circumvent the clerk of the weather and expedite work generally, such as by making hay without sunshine and the curing of crops in the ricks instead of by stooking in the fields. The author has made very considerable progress in this process since he last read a paper before the Institution and he can now treat the largest commercial ricks. Further, no internal structures are now needed within the rick, which greatly facilitates both the process of making the rick and the work of the farm labourer who has to cut and truss the hay before use. The underlying principle has been corroborated by the Ministry of Agriculture and the Oxford Institute of Agricultural Engineering, who have carried out a great deal of most useful laboratory investigation. Owing to the fact that it is possible to treat straw crops in the rick, the harvest fields can be ploughed earlier, as they should be. Further, the damage to the stooked corn by weather and vermin is eliminated. Again, the quality of the grain treated in this new way is greatly improved; a better milling wheat can be obtained, a superior malting quality of barley is produced, oats have a better appearance, whilst peas can be so treated as to retain their green hue instead of having their more usual blanched appearance.

Electro-silage.—Whilst the only electrical method of making silage in this country exists on the farm of the author, the process has made great strides on the Continent, where many hundreds of such silos are now in existence. The electrical method has proved a better way of preserving green fodder for the winter than the ordinary silage method. The principal improvement that has been made recently is the addition of electric tubular heaters, which are plunged into the mass of the material being treated. Previously it was the practice merely to pass a current between a live plate on top of the stack and an earth plate at the bottom. When plates only were used the current was negligible at starting, reaching a maximum in 24 hours. Now the load is kept constant during the whole time that the silage is under treatment; and the load factor of the process is therefore excellent. By the electrical method, silage is made without more than a trace of butyric acid, which, if present in sufficient quantity, is objectionable to those farmers who attempt to make butter or cheese from the milk of cows fed on ordinary silage. The current consumption with the present process averages 1½ kWh per cwt. of material.

Central manuring plant.—A few years ago a commencement was made in the manuring of Swiss fruit farms by means of stand-pipes in the orchards. These are supplied by underground mains from a tank adjoining the main buildings. In this tank is collected the urine from the cow-sheds, and, further, when the stand-pipes are about to be used old rotted manure is thrown into the tanks, the contents being agitated by means of electric motors, either by driving revolving arms or by circulation through centrifugal pumps. A force pump, taking its supply from this tank, pumps out the mixture to the stand-pipes in the orchards, from which the liquid is distributed by a hose pipe and nozzle. The

* The coulter is either a disc wheel or a cutting wedge which opens up or cuts the surface of the soil to facilitate the work of a ploughshare in turning over a furrow.

author's opinion at that time was that although this method might suit orchard or market-garden practice, the installation would be too expensive for ordinary farm work. The process has, however, since developed and to-day is found to save so much labour, both of horses and of men, that it is being adopted in general farm practice. As the distribution pipes are laid about 3 feet in the ground, comparatively cheap pipes can be employed, which greatly reduces the cost of the installation. Further, the uniformity of the mixture helps to produce uniform fertility of the soil.

Irrigation.—The mains thus used for manuring the fields with liquid manure can, of course, also be employed for watering them in exceptional seasons of drought, thus enabling an individual farmer to obtain more satisfactory crops than his neighbours. In Switzerland and Germany special watering machines are attached to the stand-pipes, some of which have mechanical progression devices or, alternatively, simple methods for adjusting them to water fresh areas. The consumption of electric current for liquid-manuring and watering in accordance with this process amounts to 90 units per acre, and is therefore an attractive load from the point of view of the electricity supply undertaking. Mr. Pepys Goodchild in this country has designed even larger machines than those employed on the Continent.

Conclusion.

To obtain the utmost advantages from electricity the farmer will have to be asked to do many things in new ways. For this purpose it is essential for the engineer to make a careful study of the principles of the farmer's present methods. There are many problems, both interesting and intricate, to be solved. Difficulties are still in the way, but difficulties are made to be overcome, especially as the load is so valuable. Further, it is of vital importance to the whole nation that agriculture should be placed on a sound basis, and on this account alone the question is well worthy of the most serious investigation by the electrical engineering world.

APPENDIX.

Bibliography.

Standard electrical engineering practice is followed in supplying a rural load, hence no special literature has been published. The all-important requirement is data on which to estimate the load to be supplied. Most of the electrotechnical and agricultural journals deal with the subject from time to time. In particular, reference may be made to the following :—

C.R.E.A. Bulletin (The Committee on the Relation of Electricity to Agriculture, 1116 Garland-buildings, Chicago); *Landsbygdselektrifiering och Motorkultur* (edited by Dr. A. Ekstroem, Vasagaten 6, Stockholm); *Electro-Farming* (Electrical Press, London); also the *Electrical Review*, of London, the *Electrical World*, of New York, the *Farmer and Stockbreeder and Agricultural Gazette* and the *Implement and Machinery Review*, of London, as the editors of these journals are taking a keen personal interest in the matter.

Among publications which are intended to be of assistance to farmers and their advisers, are A. H. Allen's "Electricity in Agriculture" (Pitman's, London); "Electricity for Everybody" (Electrical Press); the "Solicitor's Handbook" (National Electric Light Association, New York). A chapter entitled "The Electro-Farmer" appears in Sullivan's "Our Silent Partner" (Eyre and Spottiswoode). The following papers and reports have also been presented on the subject :—

"Electro-Farming": A lecture before the Royal Dutch Institute of Engineers at Nijmegen, published by the British Electrical Development Association, Inc., London, October 1921.

"The Uses of Electric Power in Agriculture": A lecture before the Farmers' Club, *Journal of the Farmers' Club* (London), 1922, part 3, p. 45.

"Electro-Farming, or the Applications of Electricity to Agriculture": A paper read before the Institution of Electrical Engineers, *Journal I.E.E.*, 1922, vol. 60, p. 725.

"Electro-Farming, or the Applications of Electricity to Agriculture": A lecture before the South Wales Institution of Engineers, *Proceedings of the South Wales Institution of Engineers*, 1922, vol. 38, p. 757.

"Hay and Corn Harvesting by Artificial Methods": A lecture before the National Farmers' Union (Manchester Branch), *Preston Guardian*, 3rd March, 1923.

"Electricity on the Farm," B.E.D.A., No. 486 (with illustrations of applications at Greater Felcourt Farm, East Grinstead), published by the British Electrical Development Association, Inc., London, 1924.

"Electro-Farming Economics": A paper (No. 266), read before the First World Power Conference, 1924.

"Rural E.H.T. Distribution": A paper read before the Third International Conference on Extra-high-tension Systems, Paris, 1925.

"Electric Power in Agriculture": A report by C. Dampier Whetham, *Journal of the Royal Agricultural Society of England*, 1924, vol. 85, p. 246.

"Electricity in Agriculture": A report of the Electricity in Agriculture Committee, *Journal I.E.E.*, 1925, vol. 63, p. 838.

"Electro-Farming": A continued series of articles in the *Electrical Review* (London).

"Book-keeping Made Automatic, or Auto-Countancy": A handbook designed to assist farmers in easily keeping accurate costing and main accounts. (In the press.)

"Electro-Farming or the Applications of Electricity to Agriculture": A scientific textbook (in the press) to be published by Ernest Benn, Ltd., 8, Bouverie Street, London, E.C.

For a more comprehensive list of references, see "Bibliography of Electro-Farming Literature" in the *Electrical World* (New York), 1923, vol. 82, p. 333. Also see *C.R.E.A. Bulletin* No. 2, 15th October, 1924, and each issue of *Electro-Farming* (London).

Discussion before The Institution, 4 March, 1926.

Sir Daniel Hall : As the author remarks, we may see upon the Continent in many districts a good deal more use of electricity on the farm than we have yet met with in this country; that is to say, power is distributed more widely over the countryside and the farmers are taking advantage of it; but we must clearly distinguish between the two methods of application. We have first of all the use upon the farm of what we might call the ordinary domestic load; that is to say, the lighting of the farm and farm buildings, and the carrying out of those minor power operations such as chaff-cutting, root-cutting, pumping, and so on, and thrashing in its turn, of which the author has shown lantern slides. That is the normal kind of thing in, say, an electrified area like Southern Sweden, and many parts of Czecho-Slovakia, where the power lines have been taken all over the countryside. One will find the ordinary small farm taking advantage of the electrical supply in carrying out those particular sets of operations by means of a portable motor working from two or three points situated about the stockyard, and there is not the slightest doubt that if there were a similar distribution of electrical power over our countryside we should find the farmer equally ready to take advantage of what I may call that domestic load. That, however, is not a very heavy load for the farm. What load can be picked up by doing the operations of cultivating the land? What prospect is there of getting the farmer to turn over from horses to electricity for many of these major operations which consume the greater part of the power expended upon the farm? Now, the author has laid stress upon what can be done in the way of ploughing by means of the various types of tool—the very large Siemens-Schuckert tool which will plough 20 or 30 acres a day, and the smaller tool which will work only a couple of furrows at a man's walking pace. What prospect is there of doing the ploughing so much more economically by the application of electrical power that horses will be largely displaced? We must beware of taking too rosy a view of the economies that we can effect in that way. The author draws up a contrast between 25s. an acre, which he puts down as the cost of ploughing, and either 2s. 6d. a day or 1s. 1d. a day, according to how many factors are taken into account when the cost of ploughing by electricity is calculated. That, however, is not at all the comparison that we have to draw. In the first instance, however open-minded the farmer may be towards new developments, one has to remember that he is bound to employ a large number of horses on his farm for all kinds of continual operations, such as carting crops and fodder. These are, in effect, the big operations upon the farm that call for the horses. Ploughing is in many respects a by-product, and a farmer who has really studied the economics of his farm operations will often point out that the ploughing comes very usefully into his scheme as a means of employing his horses when they would otherwise be idle in the winter. But he by no means regards the ploughing as the main draft upon power on his farm, and therefore in making these comparisons as to comparative costs we must beware of costing out our ploughing on the basis of a horse-day throughout the year, and imagine that we can dispense with those horses and replace them by a totally different source of power. We have in steam ploughing an extraordinary economic operation, yet though we have had steam ploughing sets at work all over the country for the past 40 or 50 years, they have not displaced the horse. Rather the reverse is taking place, in fact. Recently tractors have been added to the farmer's equipment, but after making all allowances for the facts that these have been in many cases badly designed, and in many other cases abused by those who use them, we do not find that there has been such a development of their use as might have been expected. The tractor is taken up by the farmer as a means of getting a lot of work done in a short time, but it has not displaced horses, and it is not actually, at the present time, taking a proper system of costing over the year, cheaper than the horse, having in view the fact that a certain amount of horse labour is necessary for the odd jobs of the farm. Therefore, let us be very careful about basing our calculations of economy upon costing a particular job. We must consider the costs in the light of the part the operation plays in the complex organization which a really well-run farm represents. Then there are, of course, other possibilities of which we know very little at the present time. The application of electricity, for instance, in the overhead high-tension discharge has possibly a stimulating effect on crops. We have these mysterious effects of ultra-violet rays, mercury-vapour lamps, and so on, in stimulating animal development, and even in affecting the quality of food. There are many possibilities for the future on those lines, but as yet we cannot say that they are so far forward that we can promise on their account an economic use of electricity upon the farm. Take that very effect of the overhead discharge; there has been no more difficult, no more debatable question to study. Years ago the most remarkable results were presented to us by various experimenters. We have been at work in this country for, I think, the past 7 years, and the results are still disappointing. Year after year we get contradictions; we are gradually sorting out the elements of the problem and are beginning to see how we can ensure a positive result, but we are by no means certain even yet that we can repeat the successes. But until we have obtained more facts, until we know, for instance, at what particular period of the growth the discharge must be applied, we cannot begin to calculate the possible economics of the process. Doubtless great developments are possible in cultivating the land by new methods of applying power—but do not let us confuse the application of electricity with farming. Farming requires the utilization of power, but the farmer does not care whether he gets his power from electricity, from coal or from horses. The question that interests him is how to use that power economically, and how to get it cheaply, and some of the author's illustrations rather confused the issue as to whether the question was

farming or whether the question was electricity. For instance, one lantern slide showed a man making a milk examination with an electrically driven machine. It really does not matter whether the machine is driven by electricity or by hand. Again, whilst it is very convenient with either an incubator or with a brooder house to switch on electrical heat, which is clean, convenient and quick, is it as cheap as the anthracite stove working directly? There is no magic in electricity; the results depend upon the man who is using it. It is easy to disparage the methods of the farmer, but he is the man who has to live by farming, and he knows that he is gambling anyhow—gambling against the weather. Long centuries of experience have made him conservative, traditional. He must be conservative and traditional, because he has no spare capital for experiments. He can run no greater risks than he already runs from the vagaries of the weather. Therefore I say he will be slow to move; he will be traditional, he will be conservative. Let us clearly bear in mind that it is the electrical engineer who must carry out the experiments. It will not be the farmer. He has too much at risk already; he is not going to be a pioneer in these particular experiments.

Mr. Ll. B. Atkinson: It is about four years since the author gave his first paper before the Institution on electro-farming. He then brought us up to date as to what was being done, and he has carried us forward somewhat to-day. If in this further record we feel, perhaps, rather disappointed as electrical engineers that the actual progress he is able to record of the work done in this country is rather small, I think we must not, bearing in mind the shortness of time, too readily lose heart, because really a great deal has been done—more, perhaps, than appears from what he has shown us of work in this country. As Sir Daniel Hall has already remarked, farmers are, like all peasants who are rooted in the soil, necessarily very conservative, very slow-moving, and indeed for the most part are anxious not to turn over from the methods to which they have been accustomed, to new methods. So we must slowly carry them with us; and furthermore we must recollect that the engineers—at all events, the electrical engineers, who are dealing with this problem from the engineering and electrical sides—are under the disadvantage for the most part of not having had an opportunity of closely studying or getting saturated with the ideas which are at the basis of farming and agricultural work. We therefore bring the two groups together, each of them looking at the problem from a different point of view, and each of them very largely ignorant of one side of the problem that has to be dealt with. There are two outstanding fundamental facts which, from the electrical and the engineering points of view, have to be dealt with. The first is that it has been proved to be easy—where there is a supply—to get farmers to take up the supply and use it for most of the purposes that the author has shown on the cinematograph films. They use it because, although it is true, as Sir Daniel Hall said, that some of these things could be done as well in some other way, they cannot be done as cleanly and simply in any other way. This, however, leaves the real problem—the distribution of electricity to the farmers—to be solved. The author has pointed out that we must not take the square mile, but the mile of route, and it has been clearly shown that where there are many houses and villages on the road to be lighted and supplied, the mile of route in most cases, if worked energetically from a salesman's point of view, does provide a load for which it is worth while for supply undertakings to run lines if they are not too expensively constructed and designed. But the other point on which we have to fix our minds is that we must get this power for the cultivation work brought into use in ways that I think we have not yet really touched. Those large-scale ploughing experiments and ploughing work about which the author has told us are all very well in certain parts of England and a great deal of the Continent, where there are no hedges, and where the fields are very large and very open, but, as has already been pointed out, on very few of the farms of this country can that large-scale ploughing with big and multi-shared ploughs be used on that scale. The problem we have to solve is some form of easily handled ploughs or cultivators working on smaller areas of ground. Personally I am gradually getting of the opinion that the plough is the wrong implement for the purpose we are considering. With horses pulling slowly and with a big dead pull, it is probable that the plough is an exceedingly adaptable implement, but we are dealing with high-speed motors, and for ploughs we have to reduce speeds; and why should we? Those other cultivating machines that the author has shown us are the type of implements that are needed on the farm; of high speed, with a light cut, so that heavy pulls and weights are not called for. Their action would be rather that of a cutter than of a wedge. The difficulty will be to find out what kind of cutting tools can be used on wet ground. I think that the author has done a real service in giving a concrete worked-out case for covering a certain area with high-tension, medium-tension and low-tension lines, but I cannot help thinking that to get much further we really need fairly large-scale experiments, and I agree with Sir Daniel Hall that it is not the farmer who should make the experiments. We ought to take an area of a good many square miles, or a good many miles along a road, get it equipped if necessary by lending all the equipment to the farmers with an option to purchase it presently, get the whole thing working under the superintendence of an electrical engineer who has studied the requirements of farming, and let him stay there for two or three years so that the scheme does not collapse because the farmers do not know exactly how to maintain the apparatus. It will teach the engineers a great deal; we may hope it will teach and educate the farmers, and it will teach the supply undertakings and indicate to them what are the real possibilities of such a supply. I agree with the author's remarks on the subject of the insulation of portable lamps, because portable apparatus at 230 volts on a farm is likely to be a dangerous thing unless steps are taken to guard against danger. In regard to the question of lighting poultry laying-houses, I have done this for some years, but only this year encountered a rather curious phenomenon. Up to this year I have used the light breed, Leghorn poultry, but this year I

have used the heavier breeds, and I find that the light breeds stay down and go on feeding and working as long as the light is on, but the heavier breeds get up on the perches shortly after the sun has set, whether the light is on or whether it is not. I do not know that it affects their laying; I have an idea, but it wants investigating, that they have larger bodies and can take in more food in a given time and do not have to go on so late. The author mentions that, under the influence of light, plants grew 3 inches in a night. I do not know whether it is the universal experience, but the plants I have observed always grew in the night and hardly at all in the day. Some creepers that I was watching last year grew 3 inches every night, and scarcely ½ inch during the day, so that we must not run away with the idea that that big growth at night was actually produced by the light. I am not saying it was not, but my opinion is that plants naturally grow more during the night.

Mr. B. M. Jenkin: My remarks will be more from the farmer's point of view than the engineer's. The first thing that strikes me is the author's splendid optimism. He says that it requires imagination to put forward his views, but he has let his imagination carry him away, I think, with reference to the possible load that might be obtained from farming. He speaks (at the foot of page 802) of the 57 million acres of land which we have in this country as if it were all suitable for agriculture, but of course it is not. It includes all the rocks and woods and forests. Now there are only 14½ million acres of arable land in the country, so that if all this were electrified the resulting load, at the ideal consumption of 275 units per acre, would be a quarter of that 16 000 million units to start with; and again, 275 units per acre, I think, can hardly be said to be based on present practice. The 100 units is an exceptional case, I believe, in Germany, and must already include the 40 units per acre for dealing with crops, but to this the author adds 75 units for haulage, and I cannot think that on any farm at present the haulage is being done electrically; so that there again one would have to divide that 275 by about 4, which would bring the total demand down to about 1 000 million instead of 16 000 million units. Within the reach of how much of the arable land in the country will the lines be? Again, when it is brought within their reach how many farmers are going to take the power? If it is sound business to supply electricity for farming, it should be possible to put the case forward without this amount of imagination. It makes one feel that there is something very unreal about the author's proposals. Another point to be considered is that, in farming, one's first object is to avoid useless capital expenditure. If one is a tenant one tries to get one's landlord to supply capital for fixtures. He is not likely to supply it for installing electrical power on the farm, or for running pipelines for manure. It must always be remembered that at the present day the question is: "Can I carry on my arable farming, or must I sow down to grass?" It is useless to put a lot of capital, in the way of fixtures, into the land if next year it will be put down to grass. The farmer will purchase the cheapest possible implement. A tractor will do all the things we have seen illustrated on the cinematograph films. It does the ploughing; it transports itself; it will drive the chaff cutter and all the other apparatus. It will go to the station and haul loads. To suggest electric ploughing on a farm is to me very much like suggesting to run the cross-Channel steamers electrically, the steamer laying a cable down across the Channel and picking it up as it comes back. It can be done, but will not when it competes with the ordinary steamer. Similarly, the electric plough cannot compete with the other methods. The author refers to Mr. Dampier Whetham's Report to the Royal Agricultural Society. I think that that Report states the case extremely soundly and sensibly. It says: "Electric ploughing is therefore being abandoned in many districts on the Continent, and, for the time being, till some more efficient method is devised, or some new idea is forthcoming, it is unlikely to be successful in England." Another point is the question of rotary tillers. The author has not pointed out the fundamental difference that comes in here. In his earlier paper he gave a very interesting description of how he had put a belt-driven dynamo on his paraffin tractor, carried an electric transmission back to a binding machine (a harvesting and binding machine for cutting corn and tying it up), and how he was able to cut a great many more acres per day with that tractor than when it was done in the ordinary way. The ordinary binder was originally designed to be drawn by horses, and the power for working the knives and the canvases (for cutting and transmitting the corn when it is cut, tying it up and throwing it out in sheaves) is obtained from what is called the bull wheel. It is a big wheel underneath the binder with strakes on it, and as it catches the earth it drives all the machinery in the binder. Now, if that is drawn by a tractor, it will be noticed that the tractor with its wheels is pushing the earth back and the binder is pushing it forward so to speak, so that the earth is acting as a belt between the wheels of the tractor and the bull wheel of the binder. Is it possible to imagine a poorer medium for the transmission of power than a belt of earth? But that is how it is done. The author got rid of that loss in using the earth as a belt, by putting a dynamo on his tractor, and a motor for driving all the machinery on the binder, and transmitting the power electrically. He was therefore able to drive his tractor on a higher gear and cut a larger acreage. It would not do it when it was driving through the earth as a belt: the engine was not strong enough. In ploughing, the tractor has to get its power transmission through the earth to the plough. It is squeezing the earth with its wheels and the plough is squeezing the earth as it turns it over, and resisting the pull of the tractor. But the rotary tiller is driven from the engine of the tractor, so that the power obtained at the engine goes direct to moving the earth by these rotating tines. That advantage is beginning to be recognized by agricultural instrument makers. Last year at the Royal Society's Show a tractor was exhibited with a direct mechanical connection from the engine of the tractor to the gear of the binder, the equivalent exactly of the author's electric transmission, but it was done by universal joints and rods. This inefficient transmission through the earth is again shown in the cinematograph film where a paraffin tractor is drawing

a mowing machine. Nowadays the Fordson tractor has a connection by which the knife is driven direct from the engine, avoiding that transmission through the earth. That is the direction in which, it seems to me, the development of agricultural machinery will have to take place.

Mr. W. Fennell: On the Continent apparently a good deal of electric work is done on the farm as compared with England. That may be due, of course, to the greater intelligence of the Continental farmers as compared with the British farmer, or to lack of enterprise of the supply undertakings in England as compared with those on the Continent. I am not qualified to say which, but I think it can be said that the reason why on the Continent there is a great deal more use of electricity in agriculture is that the supply engineer is allowed to take the mains to the farmer with far less hindrance than he is here. That, I think, is the root of the matter, and I think it explains the differences between the progress being made—if indeed it is progress, judging from the remarks of some of the previous speakers—with electric farming on the Continent and in this country. At the present time supply engineers are being urged by politicians to take electricity not only into the highways but into the byways. I think we shall be doing a good work in carrying it into the country to help the farmer and the country resident. My company is connected with an area of about 120 square miles in Cheshire, and we find that the country people do want electricity, and do use it when we can take it to them, but we meet with difficulties of all kinds in providing the supply. First of all there are Parliamentary difficulties. In extending an undertaking into the country it is necessary to pass over the old boundaries and come into new areas. For this a new Provisional Order—or at least a Special Order, as it is called—is needed. A company's undertaking may be nearing the period when it can be purchased, and capital liabilities then arise for the comparatively unproductive new area. The local authorities may purchase the central undertaking and leave the company with the outside area. In order to extend over the boundary we need a modification of the "Fringe Order" which is, at present, an Order enabling an undertaking to go over the boundary and supply Mr. Jones, but the Order is so framed that only Mr. Jones can be supplied. Now, we want an Order whereby we can take up contiguous areas instead of individual, named consumers. The only alteration that is needed for that purpose is that, instead of specifying any individual, the Order shall specify an area, by reference to the deposited map. Under the present "Fringe Order" system we have had to refuse to supply a resident by whose door our mains passed, because it was far too much trouble to go through all the formality again. We also require increased facilities for running overhead lines. I appeal to those who have influence, to help the willing electrical engineer to run these overhead lines on something like a practical basis. I hope to continue my remarks at the Manchester discussion later in the month.

[The author's reply to this discussion will be published later.]

Adjourned Discussion before The Institution, 11 March, 1926.

Mr. Montague Fordham: I wish to express the point of view of a countryman, somewhat different from that put forward by Sir Daniel Hall and Mr. Atkinson. I am finishing this week a series of some 250 meetings throughout England dealing with the question of rural reconstruction. I find a growing consensus of opinion in the country districts that the future of the English countryside depends on two things, the first a good supply of electricity, and the second the use of the dung cart. A good reply to Sir Daniel Hall's pessimism will be found in his very interesting book, "Agriculture after the War," which gives what is—or at least was—his unofficial opinion. Another book of very great importance to all electrical engineers is the Report of Lady Hall's "Committee on Rural Reconstruction," which gives special attention to electricity. What is there to learn about the relation of electricity to rural reconstruction which is so important to engineers? The rural problem is this. For 100 years the country people have left the villages for the towns. That tendency has destroyed every civilization of which we know the history: it need not destroy this civilization, because we have this new power, this power of electricity, which can be used in many ways to turn the drift back. As a countryman, I ask the electrical engineers of this country to work out an effective plan for bringing electricity right through the country districts so that we may both bring our workshops out of the towns and reconstruct agriculture. The details of the author's proposals interest the ordinary village audience to an extraordinary degree. The method employed by the author, and no doubt by many others, of drying corn crops and hay, is recognized to be of immense practical importance to farmers. In February I was speaking in Buckinghamshire at 15 villages and small towns. No matter whether my audiences consisted of 6 or 600, they were all extremely interested in the details of the use of electricity, and saw in it a way to reconstruct their country life. It is now for the electrical engineers to work out the details of the application of electricity to our countryside: country people will support any proposals which come forward from so important a body as the Institution. Let us confer together.

Mr. F. H. Clough: It seems to me that the first matter to consider is how to get electricity out into the country; once we have done this the uses of electricity are bound to develop. Even if we do not depend on the farmer, there are many country residents within a reasonable distance of supply who are potential users of electricity. Many of these have their own small lighting sets; but I think that the majority of these people would be very willing to take a supply from some central station. The cost of wiring a house and the cost of generating electricity are the same in the country as in the town. The only difference is in the transmission,

which is not entirely a matter of engineering but largely a political matter. If the politicians remove the legal difficulties, I think that the engineers will be able to overcome the technical difficulties. Much is heard nowadays about proposals for running large power mains across the country and tapping off to the farmers. Obviously that cannot be done. The cost of big-capacity switches on such a main would be prohibitive. If we take electricity out to the country we must run at higher voltages, because the distances are greater; but the higher voltages need not necessarily be associated with higher power. Perhaps it might be useful to take an example. Assume a line 10 miles long with a power demand of, say, 1–2 kW per mile, making a total demand of about 15 kW. Such a line could be supplied from a 15–20 kW transformer at 3 000 volts, and the short-circuit capacity would be approximately 200 kW. Tappings would be made to the consumers at suitable points along this line. Each tapping would consist of a weatherproof switch fuse and small pole-mounted transformer, and with the limitations given above for voltage and power these tappings can be quite inexpensive. Inexpensive lightning arresters suitable for these conditions are also available. The line itself might be single-phase in the first instance, and would resemble the usual telephone or telegraph line; in fact, the same poles could be used. Satisfactory small single-phase motors are available, and later on when the power demand has increased and the line has been converted to three-phase, three-phase motors can be installed. Underground cables would not be suitable for such a line as I have described, as the cost of insulation and armouring would be too high to be economical. Touching the economics of the matter, if such a line is installed it is obviously to the interest of both the consumer and supply undertaking to make full use of it. This means a low price per unit, and I think the interest charges on the line should be kept separate from the charge for power. If the line is designed economically the interest charges per kW of demand should be considerably less than the interest charges on a self-contained plant, which is the only alternative, and the cost of power will be very much less. I think the consumer will prefer to pay his share of the cost of the line, especially if this be made reasonable, and get his power at a cheap rate, rather than pay a high rate for power. A low power rate will ensure rapid development of the uses of electricity, and many of the interesting devices described by the author will be used. I shall now show a couple of lantern slides of a disconnecting switch-fuse suitable for controlling the power supply to such a rural line as I have described, or to a small town. It has a rupturing capacity of about 15 000 kVA and works at 11 000 volts. I have not slides of the switch-fuses for individual consumers, but these are very much smaller and cheaper.

Mr. H. M. Sayers: Major Caldwell has sent me the following figures referring to the results of lighting and feeding hens at night during the winter months. With a flock consisting of 271 pullets (one-quarter light breed, Leghorns, three-quarters heavy breed) during four weeks in November last with no light and no meal after 3 p.m., these hens laid 1 182 eggs, an average of 295 per week, or 1·09 egg per hen per week. During 8 weeks in December and January, when a late meal was given at 9 p.m. with lights on for 15 to 30 minutes, the same breeds laid 6 733 eggs, an average of 842 per week, or 3·11 eggs per hen per week. There were 9 lamps each of 300 candle-power—that is, 1 lamp to 30 birds—but a flock twice the size could have been comfortably admitted to the same light. It was found that the light breed, which were about a quarter of the flock, responded to the treatment within two days, whereas the heavy breed were slow to benefit; but their performance afterwards was more consistent. It is important, once the lighting is installed, to keep it on. Owing to an intermission of three nights at Christmas time, the yield dropped from a daily average of 130 to 93 eggs; but this was adjusted within a day or two after the regular lighting was resumed. I should like to point out another possible connection between electric supply and agriculture. It is well known that about 70 per cent of the heat units of coal are wasted in the modern steam turbine. That loss is part of the cost of the most valuable form of kinetic energy. It is a by-product for which we have not found any use up to the present. The temperature of the water is too low for any industrial use and for most domestic purposes. It warms the water of the river, estuary or sea, or it humidizes the air around cooling towers, with some annoyance to the neighbours. One use to which that warm water could be put would be extremely remunerative, sending it through buried pipes and warming cultivated soil up to probably 15 or 20 degrees F. above the air temperature. I believe that in that way the effect of glass-houses would be obtained. As to the magnitude, it is only possible to make very rough estimates at the moment; probably 1 000 kW maximum load at 30 per cent load factor would suffice for an acre of land. Experiments are wanted to find out the proper depth and pitch of the pipes, and the amount of pipe area required for the necessary cooling, so combining cooling with the heating of the land. Besides warming the land, the rising warm air and vapour would defeat the radiation frosts which so often do damage in spring-time. Occasionally with strong cold winds, the top crust of the earth might get frozen. I think that in the coldest weather of South England, the earth temperature would be 50° to 60° F., well above the minimum growing temperature. It will be necessary to investigate what is the best succession of crops for the utilization of this (at present) lost heat. That is a matter which must be left to the market gardener and the food raiser; but I suggest that the market gardener would get crops the whole year round. He could choose to some extent the climate for what he was trying to grow. If it proved in some cases that, although growth was good, ripening was slow, then, as the author has shown, intensive lighting could be used for the purpose. This connection between electric supply and agriculture deserves to be thoroughly thrashed out. Experiments can be made at a very small expense; and I trust that some of the central stations which are favourably situated with regard to market-garden land will make some before long.

Mr. E. B. Wedmore: The author has worked as a

pioneer in a field which he has made his own. The problem now is how to extend this effort and get other workers into the field. Mr. Atkinson has emphasized the importance of further experimental work being done, not only at the agricultural but at the electrical end. I think that such work should be done by co-operation between all the interests involved. We have in the Electrical Research Association the machinery for carrying out co-operative research, and to a limited extent funds are available. I conceive that there is no one better fitted than the author for preparing a preliminary schedule of the sort of problems that could be tackled experimentally by co-operative effort at the present time. I hope that he will give some thought to that aspect of the subject where electricity touches the agricultural side, and communicate with the Association after he has done so. I am not quite sure how the author's scheme of employing electricity to provide artificial climate for bee-keeping and producing the equivalent of the South of France would work out in the long run against the importation of bees raised in the South of France and used on the apple crop in this country. I believe that it is only the difficulties of transport and the number of hands through which the goods have to pass between England and France that leave any loophole for the author's method of heating to be really economical in competition with the alternative that I have suggested. Already we import queen bees from abroad. One is accustomed to breeding sheep in one part of the country, fattening them in another, and selling them in another part of the country, so that the idea of importing bees is by no means to be neglected on the economical side. There is, however, another method of employing electricity for heating a bee-hive. Let us consider for a moment what is the normal procedure in a bee-hive. The temperature of the hive is high, and is maintained by the consumption of honey by the bees. Honey is a good food ; but it is on the pollen that the bees depend for the nutritive side of their diet ; and the energy in the honey is converted very largely into heat in the hive. A hive which may produce, year in and year out, a surplus of 35 lb. of honey would consume 70 lb. during the course of the year. One knows that the bulk of that consumption is for heating within the hive. There is fuel consisting largely of water, and therefore an inefficient fuel, worth possibly £100 per ton, being used by the bees for the production of the heat necessary for the maintenance of life and carrying on the work of the hive. It seems to me that this is where artificial heat could be supplied in the form of electricity. On a very rough calculation a supply so furnished continuously throughout the winter months at a cost of 1s. or 2s. a year in actual energy would represent a saving of the consumption of a very large part of the honey that is used during the winter for counteracting the effects of the cold atmosphere. The bees consume the honey when they are in a cluster, and thus the whole of the heat goes straight to the bees at an efficiency of 100 per cent. The individual bee, as soon as it has filled itself with honey, proceeds to go through a series of mechanical exercises. There are several recognized types of mechanical exercise which are used by the bee for the purpose of simply converting that honey, so that the heat is made available just at the point where it is wanted in the middle of the cluster. Various attempts have been made to heat bee-hives artificially from without ; but they are very inefficient as compared with the system that the bee has had to develop to meet the very high cost of the fuel it uses. Undoubtedly the proper method of heating is to heat from the centre of the cluster. The instincts of the bee are adjusted to deal with the circumstances which arise when heat is produced within the cluster, the outer atmosphere being at a lower temperature. Any attempt to reverse those conditions in the hive is quite against the instincts of the bee.

Colonel R. E. Crompton : I agree with Mr. Fordham that the curse of industrialism is the crowding of the workers together in insanitary conditions in the towns, and the draining of the country life into those towns. Electrical engineers must reverse that process. The paper under discussion is enthusiastic and imaginative and should therefore tend to encourage the scheme of rural electrification. So far as I have been able, I have tried to analyse some of the tables and figures given in the paper ; and I think they are extremely hopeful. I have tried to imagine the price which will be charged for electricity in the country, but the only certainty is that the price can only be low if the demand is very large and very evenly distributed. So long as large plant is doing work in which it can be only partially employed, it must be a very heavy tax on somebody, either the company which has erected the works, and which has to pay interest on the cost of the works, or, if the Government give a subsidy, which it is probable they will not do, the burden will take the form of guaranteeing interest on capital at a low rate. That being so, we must try to popularize our electrical developments among the rural population ; and I think we could learn a good deal from other countries. Electric light is used all over the great district surrounding Milan, where there is one of the oldest supply undertakings in the world. There they have cultivated the demand by giving a lighting supply at an extremely low rate, and consequently the heating demand followed. I believe the same is true all over the South of France, and the author indicates that the same thing is being done to a large extent in Germany. He has shown very many ways in which the farmer can use power. But, looking at the figures, the maximum demand does not appear to be very great. I think that the electric silo will give a large and very steady load at a very good power factor. Then, again, a considerable amount of light will be used for stimulating the production of eggs, for stimulating the early germination of seeds, and getting increased growth in the early stages. That is undoubtedly the proper method of gradually inducing farmers to use the electric supply. We are told that the industry of enriching the soil in Germany by producing nitrates from the air has assumed gigantic proportions, but the results are shrouded in mystery. Can the author give any information in regard to this industry ? He is undoubtedly right in saying that if we can aerate the soil by continually turning it over, we can largely increase the productive power of that soil. But, speaking as a mechanic and as a man who has been much interested

in machinery, I can see greater difficulties than may first be supposed in the various apparatus shown for ploughing in the fields with cables alternately wound on and unwound off the plough. We had some experience of that 26 years ago, in the Boer War, when we had to coil and uncoil the cables for our projectors. Undoubtedly some development on those lines is necessary. I think that the load factor of all agricultural districts will be approximately the same. There will not be that advantage of diversity of load factor which occurs when part of the supply for industrial districts is worked at certain fixed hours and another part is for lighting after those fixed hours, and, during the last few years, for heating and cooking after those lighting hours. The habits of the agriculturist, of the hens, of the bees, and in fact, of everybody who will be affected will be the same all over the country, so that we cannot really look for a diversity load factor unless we do something else. For instance, we might by some means or other use our plant in the small hours, say for charging accumulators for driving farm vehicles. Mr. Sayers's project is very interesting, but I do not know how he is going to use his cooling water so far away as 50 miles from the power station. If anything, his idea is an argument in favour of having small power stations distributed all over the country, which is contrary to the idea of the new Electricity Bill.

Major T. Rich: Some years ago it was brought home to me that farmers in European countries, which have been cultivated not far short of 2 000 years, have now to meet the competition of countries where foodstuffs are being sold under economic cost. In the Eastern States of the United States and in Canada much of the land has produced nothing but wheat year after year until the country is chemically exhausted. The result is that in many parts to-day they find it necessary to buy nitrates from Chili and elsewhere. I was in Western Canada about 15 or 16 years ago, and I was laughed at when I spoke about the rotation of crops. I believe that electricity will tend to put us in a position in this country to compete with that economically fallacious system. We want, however, more than super-power stations; we want facilities for distribution. We do not want an army of new officials, nor a subsidy, hidden under the name of a guarantee. In France there are many thousands of miles of inexpensively constructed rural distribution lines, running along the roadside. In England a pressure of 250 volts (alternating) to neutral is often arranged in houses, yet a high-tension line over the roadway in the country is held to be dangerous. In France the laws and regulations are founded on common sense, so far as electricity is concerned. They are interpreted by an organization called the Electrical Committee, which is largely a committee of technical and business men. This committee, which has as its secretary an engineer from the Ministry of Public Works, considers how the Acts are to be interpreted, and what is to be done in cases of difficulty. In France, though it may seem somewhat strange, the rural authority is entitled to veto the use of overhead lines; but as a rule there is but little obstruction. The pioneer lines all over France were laid along the roadside. The reason for that, especially in the North, is rather interesting. In many parts the land is held on a similar tenure to that which was customary in England under the old Norman and Saxon days before the Enclosure Acts came into being; that is to say, many holdings are made up of a number of little strips of land, scattered round a village. There was, therefore, a great deal of difficulty in France in getting wayleaves, because of the number of owners; facilities were therefore given to run lines by the roadside for a small fee per kilometre of line; and that fee is paid to the rural or other road authority. The result is that the road authorities are not hostile to the use of electricity. We learn from the paper that in many parts of the Continent 220 volts is being used for lighting on farms. That is not general in France at all. The great bulk of the supply is at 110–190 volts, although a certain amount of rural low-tension distribution is being commenced at 220–360 volts. In the North of France, and in many rural districts of France, 15 000 volts is the general high-tension distribution voltage. Once the pressure exceeds 3 000 or 4 000 volts, it does not cost much more to go up to 15 000 volts than it does to go to 6 000 or 7 000 volts. One engineer in the Bethune Colliery district has been running some 15 000-volt single-phase lines into the villages with iron wire overhead conductors. As soon as the load has increased sufficiently, the iron wire is taken down and replaced by three-phase copper conductors. A question has been raised recently as to whether there should not be an intermediate voltage to enable one transformer station in a village to supply it direct and also a considerably larger area surrounding it through house transformers; at Grenoble Exhibition last year there were shown some double-voltage transformers which stepped down from 10 000 or 15 000 volts to 660 and 110 volts. Ploughing by electricity is increasing very much, I believe, in Italy and in France; for small holdings motors of about 7½ h.p. have been used. It has been said that the use of electric power follows the use of electric lighting. One thing in which our country is probably worse off than any other country in the world is that in proportion to the cost of living, apparently, we pay more for our electric lamps than any other purchasers of electricity. It should not be so. The real value of a 2s. 6d. or 3s. lamp is about 8d. or 10d. We ought to be able to get lamps in this country, judged by the cost of living in other countries, for 1s. or less. It is all very well to talk about economies from super-power stations, but the supply of lamps at a reasonable price would do more to further the use of electricity in this country than all the politically inspired Government projects put together.

Mr. W. J. Minton: One of the previous speakers in the discussion said that the use of the steam plough is dying out in England. That is quite possible, because steam ploughs do not always plough at the required rate. Ploughing has a twofold object when turning over the ground: (1) to provide fresh soil for the next crop and (2) to kill the weeds. At 10 m.p.h. the plough will not do that. The farmer who is a business man is dissatisfied and says the contract has not been carried out. The correct power machine to use is a cultivator, which breaks up the soil and sub-soil in the same way that an

allotment holder digs 2 spits deep. This should be done every 5 years and is work too heavy for horses. I think it ought to be pointed out to the British farmer that he can get a " snatch " crop with the aid of electric power. In one case a farmer who went 50 miles to fetch a huller to get a snatch crop of clover seed made £500 extra profit. The British farmer must cultivate more snatch crops, and electricity will help him to do this. Has the author had any experience of laying tram-lines over farms ? This would justify an overhead conductor to supply power for general use, including the tractor whether it is on or off the tram-lines. One potato farm in the Fens has tram-lines running round it; and it has enabled the owners to make a large fortune out of that farm. Does he advocate the single overhead conductor with an earthed return or an insulated return lightly buried ? In my opinion we shall have to develop high-tension direct current, and I expect that its use will shortly be increased in England. The author does not mention the comfort of the farm labourer. Get the labourer to have a few lights in his cottage, and he will be as enthusiastic as his master to get electricity on the farm. Supply the local District Nurses' Association with apparatus so that nurses can compare farms with and without electricity. There will not be a general demand for electricity on the farm until the actual men who are going to use it are enthusiastic for it. Occasionally it is hinted that the farm labourer has not much intelligence, but on one particular farm of which I have knowledge an ordinary farm labourer takes the petrol tractor down, decarbonizes and rebushes it, making a very satisfactory job. We must convince the farmer that his business is an engineering proposition. Manufacturers have to contend with a law of supply and demand quite as variable as the weather, and there is a gap of 2 to 3 years between the manufacture and use of a stock article. Farmers must produce finished articles, not raw materials for others to reap the benefit. That will be the way to prosperity.

Mr. W. A. Turnbull : A few years ago the author visited Aylesbury and delivered a lecture on farming and the use of electricity on the farm. I am pleased to say that the Aylesbury Council have placed an order for rural electrification round Aylesbury and I feel that this result is largely due to the author. The cost of overhead lines works out at £600 a mile. That is what we had to pay for a short length about 18 months ago, but we are now getting them erected for less than that. I still think that 11 000 volts is a good transmission pressure. It is possible to obtain a good 10-kW transformer at 11 000 volts (single-phase) to tap off for farms. It is my intention to tap off any farm I can, but if the pressure adopted is 20 000 volts I am afraid it will be out of the question. I am putting up steel branch lines at 11 000 volts. Such lines will easily carry 200 kW. The usual load is only about 20 kW, and if a day load does develop, a voltage-drop does not matter during the day. Later on, as the load develops, the copper main transmission lines can be taken down and replaced by steel-cored aluminium lines at 11 000 volts, which will considerably increase the capacity of the line on those same poles. The cost of the steel line is just about half the cost of the copper line, and in time I think the cost of overhead transmission will fall to £300 per mile, which will be a good proposition for the electrification of rural areas. For the wiring of cowsheds I am thinking of devising a simple vulcanized-rubber system on porcelain cleats, as I think this preferable to steel tube. I should like the author's opinion on this project.

Mr. R. H. White : Can the author give any information in regard to wind-driven generators, which I believe are now being used very largely in Germany for the production of power for agricultural purposes ?

Mr. A. H. Allen : I should like, in view of some reference which has been made to the necessity of cheapening distribution, to emphasize that point as much as possible. We hear repeatedly from engineers in the country that they cannot get on with their rural distribution on account of the high cost of lines, owing largely to the regulations imposed upon them and the difficulty of obtaining wayleaves. Those are two of the most important things to be attended to in extending electricity supply into the country. With regard to those regulations, I should like to mention a point which has just arisen. We know that every endeavour is made to make the supply of electricity in the country as free as possible from danger to the person ; we try to do that by means of elaborate protective devices. Since the beginning of this month one of these cradles, put up to protect electric lines at a crossing, was swayed by the wind and broke the live wire. The wire fell into a field and unfortunately was picked up by a boy, who paid the penalty with his life. The conditions were much worse than they would have been if there had been no cradle at all. Tramway trolley wires run down our main streets at 500 or 600 volts and we seldom hear of any trouble arising from them, yet in the country it is thought necessary to have these devices, ostensibly to save life, with the result that I have mentioned.

Mr. A. E. Jackson : I should like to refer briefly to two points arising out of the discussion. One is with regard to the use of circulating water referred to by Mr. Sayers. Has he considered that when the circulating water would be most particularly required for warming the earth, namely, during the night-time, the load of the generating station would probably be at its smallest ? The other point is in connection with Mr. Turnbull's remarks about the cost of his transmission lines. The Chief Engineer of the Adelaide Electric Supply Co. recently told me that he was constructing his overhead extra-high-tension lines at a bare cost of £180 per mile, excluding standing charges, supervision charges or profit. The poles are of the reinforced concrete type, consisting of two **I** beams bolted together with concrete in between. These are spaced about 10 to the mile.

Mr. G. S. Francis : There is one fact about the financial side of rural distribution which it might be of interest to mention. Two years ago, when visiting Bavaria, I was informed that, as the supply undertaking did not care to be burdened with the cost and trouble of developing rural distribution, this work was being undertaken by farmers' associations, etc. The initial financial difficulties were overcome by the use of a financial instrument, which I think is unknown in this country, and which is described in their somewhat cumbrous

phraseology as a "State-guaranteed, extinguishable non-interest-bearing credit." It certainly tends to advance rural development if the farming community are prepared to shoulder some of the work and responsibility which, at present, usually fall on the engineering undertakings.

Mr. F. Creedy: What, in the author's opinion, is the most suitable type of current for farm work? The lantern slides which he showed were apparently of direct-current motors. One can see difficulties in transmission from the direct-current point of view. Obviously, alternating current gives greater advantages for transmission. Clearly, three-phase squirrel-cage motors are the simplest and cheapest of all, but three-phase transmission for lightly loaded areas is by no means as simple as single-phase, which can be done with a single wire. In addition to this, metering, switchgear and other subsidiary points are a good deal cheaper on a single-phase system. Without enlarging on this point at present I may say that, though rather more expensive, the single-phase motor can be made just as satisfactory as any other type. It would be very interesting if the author would, in his reply, discuss the pros and cons of the different types of current.

Mr. P. Johnson (*communicated*): The author mentioned the use of endless track vehicles on the land. I have long been convinced that such vehicles would ultimately prove to be by far the most practicable and generally applicable method of cultivation. I do not suggest that for large areas such machines would entirely displace the cable system of cultivation, especially where great depth of tilth is required, as for sugar cane and some of the root crops. I entirely agree with the author in his specification of what is required, and I suggest that it might be of interest to the members to know what is now being done in the direction of machines fulfilling in all essential respects the author's specification, with the exception of the electrical operation. A machine already in production (by the Sentinel Co. of Shrewsbury) is a steam tractor weighing about 8 tons fitted with steerable endless tracks to support the weight on soft ground. This machine will cross-plough on ploughed land without damage to the work already done, owing to the light pressure per square inch. In stiff clay soil it has ploughed to a depth of 8 in. at the rate of 4 acres an hour, turning 8 furrows at a time and giving a continuous drawbar pull of 3 to 3½ tons. No difficulty is experienced at the headlands, owing to the lateral flexibility of the tracks and the small turning circle thus obtained. A small tractor on rather similar lines but weighing only 2 tons is about to be put on the market (by Messrs. Morris Commercial Cars, Ltd.). The construction of this machine is somewhat novel, but preliminary tests appear to indicate that it will have many advantages over the more conventional types. One of the main features is that the steering wheels are at the rear instead of the front. They carry a very small proportion of the weight of the vehicle and, being close up to the track units, give it a very small turning circle. In order to obviate the tendency of the load behind the machine to prevent steering and also to counterbalance the torque reaction at the sprockets tending to impose too much weight on the rear wheels, a novel arrangement of drawbar has been designed for this vehicle but has not yet been actually tested. The drawbar is so designed as to pivot on a vertical spindle close up to the centre of the machine and is then carried over the rear wheels so as to swing clear of them and, if necessary, assume extreme angles up to 90° with the longitudinal centre line of the vehicle. Coupled with the lateral flexibility of the tracks, this enables short turns to be made at the headlands and provides against any interference with the steerage due to the load behind. Alternative positions for coupling up to the plough are arranged on this drawbar in the vertical plane, and by coupling low down on it the tendency of the torque reaction of the sprockets to put excessive loads on to the rear wheels can be neutralized. It is suggested that there would appear to be no insuperable difficulty in adapting such tractors as the above for electrical operation.

Dr. B. A. Keen (*communicated*): I am not competent to pass any opinion on the first two sections of the paper, which deal with technical matters connected with the supply of electricity. However, the third section—Work on the Land, and Haulage—directly interests me, as for some years past we have been making at Rothamsted a study of soil-cultivation processes. My main comment is that the various possibilities cited by the author are largely independent of the particular form of power employed. With the exception of the electrical method devised at Rothamsted for reducing the friction between cultivation implement and the soil, on which I comment below, the processes themselves could be—and in many cases are—carried out with internal-combustion engines and steam power. They could, of course, be equally well operated by electrical power and, granted a general extension of such facilities to rural districts, there is little doubt that they would be so operated. This is largely a matter of economics, once the very understandable reluctance of the farming community to change any given method is dispelled by actual demonstration over a period of years, and under a variety of conditions. In this connection I wish to support Sir Daniel Hall's view that the impetus, and the initial financial outlay of complete demonstration, must come from the electrical engineering industry itself. This is the only sure way, and it is in fact the method adopted by other industries having a market among the farming community. As the author points out, there is nothing magical about electricity for agricultural purposes; it is merely an alternative way of providing power. If it has considerable advantages in such matters as convenience and cost, these facts alone will ensure its increased use on the farm. However, in considering its application to work on the land, I wish to enter a plea that it should be approached from a broader angle than the comparatively simple aspect of substituting one form of power by another. Any form of power is a means to an end, which is in the present case the cultivation of the soil. We know very little about the *science* of cultivation, although the *art* has been developed to a high level by age-long experience. Were the science more developed, electric power could then be applied to the best advantage; the implements and the tractive mechanism could be developed as a

unity. It is impossible to assume that the present designs of cultivation implements are final. They have slowly evolved, with an infinitude of empirical trial and error, from the tree branch and spear of prehistoric times to their present forms, and their future designs may well show a corresponding advance on present-day patterns. There is more than a hint of this possibility in the electrical method of reducing the draught of cultivation implements. By passing a current from the coulter to the ploughshare, a film of water is deposited on the latter, due to the phenomenon of electro-endosmose. This film acts as a lubricant, reducing the friction between the share and the furrow slice, and the draught is therefore reduced. In the tests we made at the author's farm, the current was supplied by a small dynamo mounted on the tractor drawing the plough and driven by the tractor engine. When the current was switched on, although the available drawbar pull for direct haulage was reduced by the extra load imposed by the dynamo, yet the reduction in friction at the mouldboard more than balanced the loss and, as a result, the speed of the tractor increased. This result was obtained in preliminary field trials, and, with further attention to the design and position of the electrodes on the plough, there is every reason to expect results of the same order as those obtained in laboratory experiments, i.e. a reduction in draught of 25–30 per cent. The increase of speed when a reduction of draught is achieved by any means, brings out an important principle in soil cultivation and stresses the necessity of considering the problem in its widest aspects. In tests with tractor ploughing we have shown that the drawbar pull only increases slowly for a considerable increase in speed. Thus an increase from $2\frac{1}{2}$ to 4 m.p.h., which would mean a 60 per cent increased area ploughed in a given time, was accompanied by only a 7 per cent increase in drawbar pull. The cost of the extra fuel needed to sustain this increased pull could only be a small fraction of the saving in labour costs due to the extra work done in the given time, and, in addition, the ability to complete work at a rapid rate is of immense advantage to the farmer, especially in unfavourable seasons. In practice, limits are set by the bad work of the present implements travelling at high speeds, and by the heavy wear and tear on the tractor. In the case of electric power, the question of design for a high speed of travel should be comparatively simple, in view of the inherently robust nature of the motors and the almost entire absence of complicated moving parts. Nevertheless, if attention were concentrated on this, to the exclusion of the equally important question of the design of the cultivation implement itself, the chance of a successful outcome would be very slight. The design of the cultivation implement to fulfil these requirements may at first sight appear entirely a matter for the agricultural engineer, but this is by no means the case. If he is to be in possession of a complete specification he must have much more information on the physical properties of the soil than at present. The Rothamsted work is directed to this end; its aim is to obtain, for soil, information of the kind that, under the collective title of "properties of materials," the engineer already has for the various metals, etc., used in the implements. This information is of especial importance when the possibility of a new form of tractive power is considered. It enables the designer to consider the prime mover and the implement as a coherent whole. The alternative is empirically to adapt existing implements to the new tractive force, as was done, for instance, when the internal-combustion engine came into use for land work. The early vicissitudes of this change were as much, if not more, the fault of unsatisfactory implements as of incorrectly designed tractors.

Mr. W. E. Poole (*communicated*): I think that the author presents a case the supply undertakings would be delighted to believe might be true, but the amount of electricity he suggests as a possible demand seems to me beyond what it would be wise to count on when reckoning the financial side of the overhead lines and other equipment necessary to take a supply to an average country district. If such amounts could be sold, even after a few years, we might not trouble about the high cost of overhead lines due to the high standard required by the Commissioners or the super-safeguarding demanded by the Post Office. Those of us who are connected with the business of erecting overhead lines on a self-supporting basis are basing our figures on very much smaller demands from the farmer and the country dweller than the author suggests, and we find it impossible in very many cases to show how the most simple line (complying with regulations) can pay its way. The cheapest three-phase line complying with the regulations costs not less than £500 to £600 per mile, and if it encounters Post Office lines a further £100 per mile must be added for unnecessarily elaborate guard nets, and I am of opinion that if the wish of the Commissioners as expressed, I think, by Sir John Snell some time ago, that "Electricity should be available to every house in the kingdom", is to be realized, we must have a drastic revision of the regulations with regard to secondary lines—sacrificing somewhat the reliability of the supply to the individual consumer or small group of consumers but safeguarding the main supply—and a much more reasonable attitude on the part of the Post Office. There are in some parts of the country secondary lines which are very far from complying with the present regulations, but they afford a supply to consumers who would otherwise have to go without. They do it with a reasonable efficiency and they have proved themselves safe from the public point of view. Why should we then insist on something more costly and more elaborate, and add several pence to the cost of the unit?

[The author's reply to this discussion will be published later.]

North-Eastern Centre, at Newcastle, 8 March, 1926.

Mr. J. M. Heslop: The paper deals with quite a new application of electricity. The author says in his opening remarks that the consumption of electrical energy on American farms amounts to 850 million h.p.-hours per annum, that is to say, approximately 640 million units per annum. This seems a very large

figure, but of course the United States must be considered as a Continent rather than a country and, as their total output of electrical energy is approximately 64 700 million units per annum, it would appear that the consumption for farming purposes is only of the order of 1 per cent of the total. In consequence, it can hardly be said that the farming load is at present very much developed in the United States. There is something to be said for the author's suggestion of calculating revenue and consumption on the route-mile basis rather than on the basis of the square miles of area served. After all, railway receipts are quoted in terms of the train-mile or passenger-mile. I cannot agree, however, with his figures for minimum profitable return. He quotes 5 000 units per annum per mile as being profitable, but I am afraid this is very much too low. If one assumes that a high-pressure overhead line can be erected for as little as £500 per mile—and this is much below prices which I have seen recently—then interest and depreciation alone would represent 2d. per unit on the minimum consumption mentioned. It would seem, therefore, that a minimum consumption of 20 000 units per annum per route-mile is more like what is required to ensure the commercial success of a projected rural distribution line. It cannot be gainsaid that the whole subject is one of paramount importance nationally, inasmuch as we spend abroad every year something over £500 000 000 for foodstuffs, i.e. approximately £12 per annum per head of the population. If, therefore, the use of electricity is going to result in an increased yield of home-grown foodstuffs per acre under cultivation, the benefit is at least three-fold. The farmer will get a greater return for his labour, the individual member of the community will benefit, one hopes, by a decrease in the cost of foodstuffs, and the community as a whole will benefit by an improvement in the trade balance of the country. It seems clearly established that the use of electricity for agricultural purposes results in very definite improvements in the yield of produce. From information published in the technical Press, one gathers that the electrical stimulation of plant growth yields increased crops up to 50 per cent in the case of grain, 25 per cent for mangolds, 33 per cent for sugar-beet, 50 per cent for carrots, and 90 per cent for strawberries. Electric ploughing, it is claimed, results in a 20–25 per cent bigger crop yield, and electric thrashing, the author tells us, yields 5 per cent more grain than existing methods. This, it seems to me, furnishes the basis on which the problem should be attacked. Taking the case of wheat, apparently we import every year wheat to the extent of 220 million bushels, and we raise at home approximately 57 million bushels, making the total requirements of the country 277 million bushels, or approximately 6·6 bushels per head of the population. The average yield per acre by present methods of cultivation is of the order of 31·5 bushels. Now, if electric ploughing gives 20 per cent crop increase, electro-culture gives 50 per cent increased yield of grain, and electric thrashing yields 5 per cent more grain from a given crop, then it seems reasonable to say that 31·5 bushels per acre could be increased to $31 \cdot 5 \times 1 \cdot 2 \times 1 \cdot 5 \times 1 \cdot 05$, that is to say, to approximately 60 bushels per acre. If that be possible, then the acreage required for 277 million bushels would be rather more than 4 million acres, or a little more than twice the acreage at present under wheat. Again, the current price of wheat is approximately 6s. per bushel. A yield of 31·5 bushels per acre at 6s. a bushel gives a return per acre of £9 9s., whilst 60 bushels per acre at 6s. a bushel gives a return per acre of £18. If the farmer can be shown how to increase his yield per acre from £9 9s. to £18, then I have no doubt he will be not only willing but eager to electrify his farm. The author is, I think, the man to do this and he may rest assured of the hearty co-operation of the supply engineer, in view of the size of the potential market for energy. The author takes a figure of 275 units per annum per acre as possible under ideal conditions, and proceeds from this to calculate the potential agricultural load of the country as 16 000 million units per annum. This, of course, is most attractive for the supply engineer looking for fresh markets, but, unfortunately for the author's case, and still more unfortunately for the supply engineer, the whole 57 million acres of land comprising this country are not all agricultural land. Only 32 million acres are under cultivation, and of these, some 18 million acres are permanent pasture, leaving 14 million acres under crops, divided roughly as follows: 7 million under corn crops, 3 million under grain crops, and 4 million under other crops and grass. Now, on page 803 the author gives as probable consumptions:—

General uses	10–30 units per acre
Ploughing and cultivation ..	45–60 units per acre
Total	55–90

or a mean of, say, 75 units per acre, which for 14 million acres = 1 050 million units per annum. Then there is a thrashing load of 24–45 units per acre, or a mean of, say, 35 units per acre. A consumption of 35 units per annum per acre for 7 million acres under corn crops = 245 million units per annum, or a total potential consumption for agricultural purposes of 1 050 million plus 245 million = 1 295 million units per annum, which is very much less than the author's figure of 16 000 million units per annum. To illustrate the point, I know a factory where, in one small shop 90 ft. × 30 ft., the consumption amounts to 90 000 units per annum. This is equivalent to $1\frac{1}{2}$ million units per annum per acre, but that does not justify me in saying that the potential consumption of electrical energy in the country for manufacturing purposes is $1\frac{1}{2}$ millions multiplied by the 57 million acres which constitute Great Britain. I am sorry that the author has taken such a figure, because I feel that it is definitely open to objection as being misleading. It is not valid to take the total area of the country as being agricultural land, neither is it necessary to adopt such an argument. A potential energy market of 1 295 million units per annum is well worth serious consideration without inflation.

Mr. R. E. Robson: Farming, in addition to being the greatest and oldest industry, is also the most conservative, and it is very difficult to make any headway with the North Country and South of Scotland farmer. The easiest types of farmer to persuade to introduce

electricity are the gentleman farmers, the dairy owners and the breeders of valuable stock. I should like to ask the author what he considers to be a fair price for current on farms. In my opinion, the suggestions of the Electricity Bill now before Parliament have set back the advancement of electricity in rural districts. Farmers and country residents now think they can get cheap and abundant supplies of electricity almost immediately, whereas it will be many years before they can be supplied in most districts. The idea of procuring a cheap supply immediately is preventing the sale of private plants to many intending users. The private plant on farms is the pioneer for a public supply, and far more encouragement should be given to the publicity and advertising of private plants than is given at present. Once a private plant is installed, as soon as the supply undertaking is able to supply current the customer is already trained to the uses of electricity and is anxious to get more electric power. There are nearly 20 uses to which electricity can be put on a farm, even from a 2-kW set. With regard to mechanical ploughing, I believe that there are a large number of farmers who specially breed horses and wish to use them for ploughing. I also understand that thrashing is done to a large extent by contract. With reference to e.h.t. transmission lines, if we take a district such as that between Newcastle and Edinburgh there is very little load to pick up, as there are very few towns and not many villages. I am somewhat astonished at the author's suggestion of tapping 33 000-volt lines in a temporary manner, and I should like to have more details as to how this is carried out. What load are the tappings carrying where this is done abroad? I agree with the author's methods of running cables in farm buildings and confirm that I have found ordinary vulcanized-rubber cable run on cleats very satisfactory. I am against the use of hand-lamps where a fixed light could be used. Does the author consider mechanical milking to be satisfactory? A friend of mine, an electrical engineer, once used it but eventually gave it up.

Mr. T. Carter: As the sting of a scorpion is in its tail, so is the point of the paper to be found at its latter end. Agriculture should undoubtedly "be placed on a sound basis," for our national safety in any time of difficulty depends greatly on the extent to which we can feed ourselves. However sound may be the counsel to buy in the cheapest market, the process cannot be successful unless a long view is taken of the real meaning of "cheapest"; and the temporary advantage of low cost of agricultural produce brought from abroad when things go smoothly is a poor thing to set off against a possible failure of supplies in a time of trouble. To be self-contained is a thing worth paying for, because it will be cheapest in the long run, and may prove to be of literally vital importance. But it is difficult to convince people at large that the proverbial rainy day will ever come, and hence the importance of cheapening agricultural production in this country is extraordinarily great. To continue a phrase of the author's, if we are not in the van we may find ourselves in the cart. The author refers to the individualistic tendency of the minds of farmers in this country, and it is therefore particularly necessary to convince them that it will somehow benefit them to adopt his proposals. Otherwise they will hesitate before they arrange to do things in new ways, or to alter the existing routine of their work. I should like to put forward a few questions and comments with a view to making some points clearer through the author's reply than they appear to me to be in the paper. The farmer is said to prefer a fixed charge plus a low rate per unit. I think this depends on the amount of the fixed charge; one farmer friend of mine, at least, objected very strongly to what he thought an entirely excessive demand. However that may be, the basis of price used in the paper is not obvious. Table 1 seems to be founded on 3d. or 4d. per unit, and not on a fixed charge plus a unit charge. The 275 units per acre mentioned as a possible consumption would thus cost something of the order of £4 per annum; and if the rent of the farm is £1 or £2 per acre per annum, the farmer will need to be convinced that he will get back, in return for this (to him) considerable expenditure, as much as will make it worth his while to incur it. I do not know whether rural methods of book-keeping are of the most accurate; and if it is as difficult to make the farmer see all that he is saving by using electricity as it is to make many other people see it, I do not envy the author his task. An important question will be how much of the cost of a transmission line should be charged to the rural supply. If the line is required for interlinking two places in any event, and the rural consumption is taken from it merely because it is there, the cost of the line is obviously not chargeable to the rural supply. I hope that a supply will not be refused to an out-of-the-way corner of the country because no line goes near it. Arrangements ought then to be made for either the supply undertaking interested in the district, or some private person or company willing to undertake the supply, to put down a local power station; and when it would be more expensive to carry a special line to a place than to erect and work from a local plant, there ought to be no hesitation in deciding on the local plant. I cannot think that consent will easily be gained to the connection of temporary loads by hooks to 33 000-volt lines. It is surely inadvisable to have things that are dangerous where there are essentially unskilled persons, even if a skilled man is in charge; and the cost of the skilled man would not be lost sight of by the farmer. The author refers to the constant raising of the standard of wiring in farm buildings; but why not simplify the whole problem by using really low pressures in these places? Not only hand-lamps, but fixed lighting too, might very well be supplied from 25-volt or 50-volt circuits, and the consequent cheapening of the wiring would be a valuable thing. It is surprising to read of motors of comparatively small outputs working successfully at 5 000 volts. They must have been expensive in first cost, and large in size compared with those that would be required for lower pressures, and it would be interesting to have fuller details of this particular equipment. I commend what the author says about the usefulness of ball bearings. They need practically no attention in respect of lubrication, one charge of grease sufficing for many months, and, if well fitted at the outset, they run excellently. The curves about eggs are interesting, but obviously the price curve

is as it is only because the great bulk of egg production is under unlighted conditions. If all poultry farmers provided their hens with the forcing plant described by the author, the taking on by the egg curve of approximately the shape of the present price curve would certainly be accompanied by a change in the shape of the price curve to something like that of the present unlighted production curve. Whether, therefore, eggs would bring more profit in the end if lighting were generally adopted, remains to be seen. What is of importance, however, is that more eggs would be produced in this country, resulting in a nearer approach to the self-containedness that I have already referred to as highly desirable, if not essential. Finally, I would refer to the suggestion that a creeper-tractor should be equipped with storage batteries, and would ask where it is proposed to obtain direct current for charging the batteries. The paper seems to contemplate the exclusive use of alternating current, and presumably, therefore, some rectifying or transforming apparatus would be required in conjunction with the batteries. This adds a complication, and increases the cost of electricity to the farmer, both because of the additional plant and because of the necessity for skilled attention to it. Presumably the author has some quite definite proposal for a means of charging the batteries, but it is not obvious from the paper how it is to be done.

Prof. D. A. Gilchrist: As to increasing the growth of corn crops by electricity, we are already, owing to improved methods of cultivation, manuring, and improved varieties, getting under good conditions as heavy corn crops as will stand. Under adverse conditions such as attacks of insects or plant diseases, the use of electricity would not give us help, nor would it be available on short notice. One of the cinematograph films exhibited by the author showed an electrically driven plough with three furrows to take furrows each 15 in. wide and 12 in. deep. I may explain that most of the land in Northumberland is lying on a boulder clay subsoil and it could not be ploughed to anything like that depth. About 80 years ago, when there was a boom in steam cultivation, much of such land was spoiled by bringing the poor subsoil to the surface. As to a point made in the discussion that the best farmer was the gentleman farmer and a man who had another business as well, this certainly is not my experience; in fact the bulk of our farmers are ready to adopt a good thing when it is placed before them. A Hexhamshire farmer, now in New Zealand, stated in a letter to me to what a large extent the farmers there are making use of electricity. We should get full information as to what is being done in that country. I believe we are ready to make considerable use of electricity on the farm in this country if it can be done at anything like the cost suggested by the author. I believe that a good ploughman and a good pair of horses are still of great value on a farm. During the war, tractors were put on the land, but unfortunately this was done hurriedly so that it was difficult to chose the best type of tractor and to work it as it should be done. For this and other reasons the use of the tractor is not being continued in many cases. As to a statement in the discussion that thrashing is all done in a few days at one time of the year, I may point out that this is not desirable and that thrashing operations are distributed over a considerable part of the year. I should like to see a really good farm selected where an electrification scheme could be carried out in co-operation with the Institution. Mr. Elliot, of the Northumberland Farmers' Union, who is present, would, I am sure, assist in the selection of such a farm. If you approach us in this way we should have the conditions quite clear as to what the total cost will be, and it should be done in such a way that it will be a demonstration of how it can be brought within the reach of any farmer. The author has shown cinematograph films of electrically-driven milking machines, but in clean-milk competitions it is frequently found that hand-milking under proper conditions is most likely to give the cleanest milk. Statistics as to acreages of farming land in this country have been given by one or two of the speakers, but we must remember there is much land that cannot be profitably farmed under arable conditions in this country.

Mr. W. F. T. Pinkney: With reference to Table 1, showing the units and revenue per mile of route, it will be noted that in the comparison of the consumption of energy between rural and urban areas, for rural areas lighting, cooking, heating, and barn work on farms are taken into consideration, whereas in the urban area lighting only appears to be considered, the consumption in the urban area being 200 units per annum per consumer. I have some recent figures available for just under 100 houses where the average consumption is over 2 000 units per house per annum, so that a very much higher consumption than 200 units per annum should be considered in the case of the urban areas, and it may very well be argued that the figure can easily be increased by 10 times. There is a great deal to be done in the direction of applying electricity to agriculture, and it will be very desirable to get some farmer in this district to have his farm equipped electrically, so that we can satisfy ourselves as to the economic value of it, and also demonstrate the value of other appliances. The author suggests, under the heading "Distribution System," that it will undoubtedly be the practice in rural areas to work with a greater voltage-drop than will be permissible for city work, and I should like to point out that, however desirable this may be, the existing regulations absolutely prohibit any appreciable variations in voltage.

Mr. J. A. Anderson: From the farmer's point of view electric power supply in and about the farm buildings would be very desirable, and Fig. 10 gives a fairly comprehensive idea of the uses to which electric power could be adopted for power and heating, in addition to which there is always the lighting of the farmhouse buildings and cottages. From this load alone, however, the power supply undertaking would be disappointed with the results, particularly if a supply were given at a low price per unit. On a good arable farm of about 400 acres the thrashing and crushing-mill motors would probably be used only about 10 hours a day for about 60 days in the year. The chaff-cutter and root-slicer would probably be used about ½ hour every day, so that as far as the load in and about the farm buildings is concerned the load factor would likely

be a poor one on any individual farm, and I doubt if it would be as good as that shown in Fig. 5 for a mixed dairy farm. It would, I think, only be in very exceptional cases where the 35 per cent load factor mentioned by the author at the foot of page 803 would be obtained in this country. If a number of farms were connected to the same line and if arrangements were made for different farms to thrash or crush on different days, the load factor on the whole would be improved. This arrangement would, I think, be preferable to the cutting off of the cooker and other plant on thrashing-mill days. The bulk of the farming done in this country consists of growing grain, hay and root crops, and feeding stock. The making of butter and cheese, and the production of eggs and vegetables, are more or less dependent upon local conditions, and I do not think that the electrification of farms will make much headway until the work on the land can be done by mechanical means. When that time comes, if it is done by electric power the supply undertaking will not, I think, have much cause to trouble about load factor during the working hours of the day. To me the most interesting part of the paper is that dealing with the work on the land and haulage. As far as cultivation is concerned, the author gives a fair idea as to how this part of the work could be dealt with, although I am afraid that the Home Office Regulations would prohibit the use of 5 000–10 000-volt motors and trailing cable in this country. Under the heading of "Small Electric Plough" the author describes a plant requiring 25 h.p. Judging from the size of the motor I should have thought that a plough of this size would be capable of ploughing 20 to 30 acres per day of 10 hours. This acreage would, of course, depend on the depth of the furrow and it would be interesting to know what horse-power is required for the large plough mentioned on page 809. It would also be interesting to know the limit of weight per square foot to prevent hard pan from being formed. Can the author give any information in regard to any attempts which have been made to handle crops mechanically, such as stooking, picking up stooks and stacking, turnip thinning, topping and handling, potato digging and lifting? In regard to harvesting, many crops, owing to their bulk, have to be cut one way, and the return journey with a mechanical vehicle could be travelled at a higher speed. I think it would be easier to the engineer in tackling this problem to take little or no account of the existing implements on a farm. The engineer's ideas would be very much cramped in doing so. No doubt it will be tried, as was done in the case of the development of the motor car, but the motor-car designer soon dropped the idea of converting old dog-carts or phaetons into motor-cars by the addition of a petrol engine and gearing. It should also be realized that it will not generally be an economical proposition to introduce mechanical appliances for any particular section such as cultivation, and until all the operations on a farm can be handled mechanically little progress will, I think, be made. Particular attention should therefore be given to the handling of crops. The author mentions certain districts where the steam plough has made progress. Without knowing the localities, I imagine that the land in these particular districts is of heavy clay. I am acquainted with a farm in Scotland consisting of 500 acres of very heavy clay land where steam ploughs were introduced successfully. The farmer was able to dispense with 7 or 8 horses, but on most farms under cultivation to-day no reduction in the number of horses would be possible by the mere introduction of mechanical cultivators. When all operations on a farm can be handled mechanically, I see a great future for the more extensive farming of land in this country. One would more readily appreciate this if the author gave comparative food values of different crops. As a rough estimate I should say that a grain crop produces 3 times as much as grass land, and root crops 9 times as much. Taking a broad minded view of the matter, one has to visualize the future farm to be one consisting of 2 000 to 3 000 acres with fields correspondingly large. The economical size of the farm should be in proportion to the capacity of the units. The author mentions a cultivating plant capable of dealing with 27 acres a day, corresponding to the work done by about 14 horses or, say, the number used on an arable farm of 500 to 600 acres. Using, say, 5 such units with one spare, I estimate that the most economical size of farm would be about 2 000 acres. Unless the size of the present farm, which generally consists of 300 to 500 acres, is considerably increased, the capital cost of installing mechanical appliances would, I think, be prohibitive. It is interesting to note the different appliances which have been adopted on the farm by an electrical engineer who has turned farmer. The lubricating effect of passing electricity between the coulter and ploughshare is particularly interesting, but I should like to know if the author puts the proposition forward as a practical and economical one. It would be interesting to have some figures in connection with this. The value of the paper would also have been enhanced if the author had given figures as to the cost of installation and operation of crop driers. In this connection the farmer can usually gather the whole of his crops in fairly good condition except once in about every 10 years. The crop driers would free him from a certain amount of anxiety, but I do not suppose he would be willing to pay much for this. I should also like to know if the crop drier is capable of producing hay completely dried, as is done in the northern counties and in Scotland, or if the hay can only be cured in the manner generally adopted in the south, where it is not completely dried before being put into a stack. The figures in regard to poultry and bees indicate that turning night into day for the hens and the bees is a paying proposition. From the load-factor curve given in Fig. 12 it would appear that electric power is used to some extent throughout the whole 24 hours. In regard to electro-silage, does the method cited by the author prevent the considerable amount of waste which was experienced by the old method of merely applying pressure to the fodder?

Mr. L. C. Grant: The introduction of electricity to a farm and the high cost of the service are probably the greatest difficulties. Farmers cannot understand why a high-voltage line crossing their land cannot be tapped easily. It is almost useless to talk to them of the cost of high-rupturing-capacity switchgear, high-voltage transformers and so on. Distribution through

a cheaply-constructed line at 3 000 volts or under seems to be one solution, provided that there is a possibility of the district being worked economically at some future time, but, even so, the scheme has to be financed and finding the financier is no mean task. I often think that something could be done with the present high-voltage cross-country aerial lines at 6 000 volts and above. In this district we have 20 000- and 66 000-volt lines which are crossing farm land for the greater part of their routes. To tap these (for a farm) in the orthodox way by means of switchgear and transformers is almost impossible. Switchgear of considerable breaking capacity must be used and the general engineering must be up to a good standard. I have been investigating the question of tapping such lines by means of condensers with or without transformers. If condensers are used, no switchgear is required, except perhaps for isolation, and the transformers, if used, can be built for comparatively a low primary voltage. Condensers suitable for up to 500 000 volts (R.M.S.) have been developed recently. At this voltage and at normal periodicity such condensers are capable of passing a usable amount of power, and as the purchase price is but a fraction of the cost of switchgear, it seems to me that something might be done, at any rate in the early stages of development, to give supplies in this way. Artificial hay-drying seems to be a promising field as a means of introducing electricity to the farmer. Here there is a load of the order of 10–20 h.p., and to make hay in this way removes one of the farmer's greatest anxieties, namely his dependence upon the weather for hay-making. Against the cost of the energy for the heater and fans can be placed the cost of handling the hay while it is lying in the field, and the decreased risk of damage while the hay is lying out in the field. The additional cost of carting undried hay to the drying apparatus seems likely to have some bearing on the economics of the proposal. Egg production by means of artificial lighting seems to be a reasonable proposition and, of course, the provision of electric light and small domestic appliances in the farmhouse appeals to the imagination of the farmer—or his wife—and is likely to be of considerable help in the early stages of development. The introduction of a small petrol-electric lighting set for this purpose is a good way of demonstrating the possibilities and might pave the way to greater developments. I think that the artificial treatment of seedlings and the rapid development of plants by means of artificial light is a subject of great interest and should be brought to the notice of interested persons. The scheme is helpful both to secure rapid development of early flowers for the market and also to ascertain if a newly developed variety is likely to revert. Seven days' energy consumption at 6 hours per day and 1d. per unit gives a cost of 3s. 6d. to produce flowers in 7 days. Has the author any recent information in regard to the economics of milk treatment by ultraviolet rays ?

[The author's reply to this discussion will be published later.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 10 MARCH, 1926.

Mr. F. J. Moffett : On pages 808 and 809, instances are given of the value of lighting in increasing egg production, stimulating plant growth and encouraging bees to produce a larger output of honey. In the latter case the use of heat as well as light is advised. It appears to me that the application of heat would greatly assist in many directions other than increasing the yield of honey. If poultry houses were heated to a moderate temperature in addition to being artificially lighted, it is reasonable to suppose that the output of eggs during the winter would be even better. On the subject of the stimulation of plant growth by means of low-grade heat, I have received an interesting letter from Mr. H. M. Sayers, who suggests that the warm circulating water from electricity generating stations could be used to warm the soil and neutralize the effect of the spring-time frosts. He calculates that the surface temperature of one acre would be raised 10 to 15 deg. F. above the air temperature, for every 1 000 kW of load on the power station, and that this temperature would enable the crop to grow during the winter and take full advantage of the spring sunshine. Apart from the use of heat for poultry houses, beehives and stimulation of plant growth, there is a considerable heat demand in the farm house, particularly in the kitchen, stables, cow-sheds, piggeries, etc., both for warming the buildings and heating the food. The cheapest way to provide the bulk of this low-grade heat on a farm is to use a self-contained generating plant driven by either a steam or internal-combustion engine, and to utilize the heat which would otherwise be thrown away. In the case of the steam engine there would be the heat units in the exhaust steam, and in the case of the internal-combustion engine the heat in the jacket water and in the exhaust gases. The author does not mention self-contained plants for the generation of electricity on the farm, probably on account of the difficulty of skilled attendance, but such generating plants, at any rate in the case of those driven by internal-combustion engines, can be made almost automatic in operation. In any case, for the handling and upkeep of electrical gear there must be someone with a certain amount of engineering skill. There is no doubt in my mind that if the heat which is usually thrown away during the generation of electricity were made use of, the self-contained plant would give the best results from the point of view of running costs. If the use of electricity on the farm is to wait for the establishment of rural transmission and distribution systems throughout the country, it will be many years before many of our farmers in the more remote parts of the country can hope to obtain a cheap supply of electricity.

Mr. F. Forrest : The author has not dealt with the question of transport on the farm, and where the area is considerable this question must be one of some moment to the farmer. It is difficult to see how electricity might assist him in this matter. It would appear, therefore, that a self-propelling machine which could be

used for transport and for driving the various farm implements would be the best arrangement from a general utility point of view, and this convenience should be set against the higher running cost of the plant. The figure mentioned in the paper read by Herr Wallem before the World Power Conference showed that the average consumption of electricity on farms in Germany varied between 6·4 and 10·4 units per acre per annum. This is an extremely small amount, and it is doubtful whether a power supply undertaking would be willing to incur much capital expenditure on transmission lines to pick up such a supply.

Mr. P. M. Pinder: The tilling machine so well illustrated in the cinematograph film appeared to be doing its work very well, but I doubt its ability to work well in a good stiff clay, as in the film this implement was evidently working in a sandy, or light loam, soil. The author mentioned in passing that a thrashing machine driven by an electric motor yielded 5 per cent extra corn; is this to be taken as a selling point, as one hears of similar points being raised in the sale of electric ovens? The author stated that ploughing was done 18 in. deep, but I think it would be impossible to plough clay soil this depth, at least as a commercial proposition. From the farmer's point of view it is regrettable that no details of costs are given in the paper, such as the capital outlay required for equipping, say, a 200-acre farm, and the average length of time required to recoup that outlay. In considering the general exodus of farm labourers into the towns, is it possible to carry out the same amount of work on a farm with fewer men after installing electric light and power in the homestead?

[The author's reply to this discussion will be published later.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 30 MARCH, 1926.

Mr. R. H. Wadsworth: The application of electricity in a town or an industrial area enables a fairly continuous load to be obtained during the day, and at night it is made use of for domestic purposes. Why cannot we have some means of electrifying the agricultural districts, so that a continuous load could be obtained from agricultural uses? This would considerably help those smaller areas which cannot afford to install electricity for the small population of householders, simply because the load is not large enough. The point that troubles the farmers to-day with regard to electricity is simply that in many cases they are a considerable distance from the distributing line and the cost of the service to the farm is heavy. A farmer may have to lay the service 500 or 600 yards, and he cannot afford the first cost. There are scores of farmers who would use electricity if the cost of installation could be reduced. The author's suggestion of employing overhead instead of underground lines would meet the difficulty admirably. The application of electricity to farms, especially milk farms, would be of great service to the consuming population of this country, because nothing would conduce more to the supply of clean milk than a good light. I should like to impress on the urban districts the importance of assisting the rural districts, because if the farmer can be in any way helped at the outset they will find it a good paying proposition.

Mr. T. Wright: Rural areas are very scattered and, as Mr. Wadsworth said, services would be most costly to lay. In our locality there are many distributing lines, so perhaps every farmer will be able before long to obtain a supply at comparatively slight expense. If the first cost can be reduced, I am confident they will not hesitate to have a supply. Electricity will certainly be a great boon in a wet summer, and it will solve the problem of getting in the hay when the weather is bad. Hay dealt with in the way suggested does, I understand, produce a first-class milk, and that is what we require.

Mr. W. J. Medlyn: On the question of cost to the consumer the paper is a little disappointing; its value would be enhanced if the author could add some information as to the cost of this form of power as compared with other methods of meeting the working requirements. The paper gives a good idea of the economical advantages of using electricity, and in the course of his remarks the author has filled up some gaps in the paper. In a general way, of course, the growth of the system is an indication that the expansion is resulting in economic advantage to the consumers as well as to the supply undertakings. The lantern slides and cinematograph films have brought very clearly before us the fact that electricity is the only method of carrying out a good many of the operations in farm work. The paper leaves the impression that much still remains to be done in the way of standardizing materials and equipment. There are many important industries, not only in the United States but in this country also, where standardization has been developed to provide for the cheapening of supplies by mass production; and it seems clear that a further extension of this principle to rural electricity supply could not fail to prove advantageous alike to supply undertakings and to consumers. There appears to be an impression (which the author rather confirms in his remarks) that Post Office engineers are antagonistic to the extension of power supplies in rural areas. This is not so. Telephone exchanges require electrical power for their economical operation, and as the telephone services are being extended to meet the requirements of dwellers in country districts, the need for electrical power supply for Post Office purposes is growing. I hope that this statement will clear away some of the misapprehension which appears to exist. I think we ought to take a broad view in these matters. In all branches of the electrical industry we are all interdependent to a great extent, and the growth of one branch reacts to the common good and to the advantage of all. Further, growth can only take place when the supplies of the commodity prove to be an economic advantage and convenience to the community; and it is certainly to the advantage of

all of us to combine to produce this very desirable result. I suppose there will always be differences of opinion as to what is a proper apportionment of charges where different undertakers are concerned. A good deal has been said on the subject from time to time, one suggestion being that supply undertakers should have a free hand in the provision of distribution lines, and that the Post Office should take its own measures for the protection of its own plant. That sounds an excellent idea, from one point of view, but we might apply the same principle to the farmer who persists in loosing a savage dog at night and tells his neighbours that they should make their sheep safe by locking them up. The need for reasonably cheap methods of construction is a pressing one, but the question of finding the best solution is too involved to be dealt with in a casual way. After sifting the actual facts, the decision as to the precautionary measures which will be required will ultimately rest with the authorities who are vested with the necessary powers. With constructive suggestions and good will combined, I think the final solution ought to be fair to all the different interests concerned.

Mr. W. Fennell: I have been asked to speak as representing the supply side of the question, in what may be termed an agricultural area. Mr. Wright and Mr. Wadsworth have both emphasized the need for a rural supply of electricity, but the author says, I think, not quite correctly that we have not learned the proper way to tackle the problem. My view is that we are not allowed to. We have to construct overhead lines in this country under regulations which were made with the chief object of applying them to transmission lines designed to supply large quantities of power at a distance. Those regulations are quite unsuitable for dealing with a rural area. I realize the great field which is open to us in rural areas, and I have tried to do all that is possible under the existing regulations to reach the farmer in Mid-Cheshire. My company recently raised a considerable sum of money largely for this purpose. We did not underwrite the issue, which was over-subscribed, and this demonstrates the public belief in this development. We have encircled our area of 125 square miles with a 33 000-volt overhead line system. We have tapped these extra-high-pressure lines and have provided outdoor substations for stepping straight down from 33 000 volts to low pressure for use in large villages, using transformers of as low a capacity as 25 kVA, on a commercial basis, and I do not think this has been done before. We are prepared to run branch lines, and indeed have already run some of them miles into the country districts at about 3 000 volts, suitable for connecting transformers for hamlets and individual farms. We have no intention of charging the farmer large sums, or indeed anything, for getting to his farm. I do not think that in the last 10 years my company has taken from all its consumers more than a total of perhaps a couple of hundred pounds for service costs. In general we rely upon reasonable guarantees. We are in the position that we are ready with our main lines and substations, and we are prepared to go into the by-ways and the lanes; but we want help from the authorities and accommodation from the Post Office in order to carry out the rural portion of the scheme. I should like now to deal with some of the more pressing difficulties we have to face apart from the regulations. Both the author and Mr. Medlyn have said that the Post Office authorities are not antagonistic. I do not think they are; they are merely self-centred. The Post Office officials naturally think of the Post Office, and I do not blame them; but they should not carry it quite so far as to ask us to pay their costs for special construction when they decide in their wisdom to follow us. For instance, in the district of Cuddington they sent us a demand for special construction costs to enable their new line to cross ours in no less than six places in a ½ mile, although they could have chosen another route. We should certainly have chosen another route if we had been following them. We do not object to pay when we are second-comers; we recognize we must pay because we cannot expect the Post Office to alter their works for us at their own cost. Again, the guarding arrangements upon which they insist may be necessary under certain conditions, but along a country road they are superfluous. When the Post Office requests an undertaking to put up steel towers to support the line, with a steel net to hang under the line to catch it when it falls, and a double line wire connected to two sets of insulators, tied together at short intervals so that it cannot fall on to the guard, it is demanding rather too much. Each of those crossings costs £300, which sum would construct over a mile of country line, but I am very glad to say there are indications that a more reasonable spirit will be shown in this direction. There is another class of the community to whom we must look to help us to get to the farmer, and that is the farmer himself. The value of land seems to appreciate to an extraordinary degree when the farmer knows that an undertaking desires to erect a pole on it. The farmer, in general, will have to realize that electricity will benefit him, and therefore he must help us in every way, and not send in heavy claims for damages. A hedge seems to cost about £5 a yard to repair when a pole has been dropped on it or we have had to cut through it. I feel sure that the farmer, when he does realize the tremendous benefit he can obtain from electricity, will be more reasonable. With regard to overhead construction in general and the methods of construction of substations, it has been to me a most fascinating business designing new and cheap forms of tapping e.h.t. lines and dealing with manufacturers, persuading them to alter their designs to give us what we want and to leave out expensive things which are not required in rural work. With regard to the line construction itself, we have several cable companies and other highly organized firms who are second to none in the world for carrying out the heavy lines, and the smaller ones are carried out by our own staff very safely indeed, at the lowest cost we can achieve under existing regulations. Those of us who have rural districts included in their areas have a very great responsibility. There is every temptation to the supply engineer to keep to the towns and suburbs where the financial return is fairly sure and where he does not encounter such difficulties as arise in rural areas. This temptation must be resisted and we should be ready to go to a good deal

of trouble to meet the demands of the farmer so that we can put this country in a better position than it is in regard to agriculture. We have also to think of the country resident who is expecting a service for light, heat and power, which we alone can supply.

Mr. T. E. Herbert: I feel that it is incumbent on someone to issue a warning note on the development of electricity in agriculture. As electrical engineers we are naturally disposed to push our own industry without considering many of the larger problems involved. I think it would be a calamity if the public were allowed to believe that the supply of electrical energy to farmers would solve the whole of their difficulties. I admit, quite freely, that the supply of electrical energy is decidedly to be desired, but very serious injury will be done if extravagant claims are made as to the benefits to be derived from it. So far as I am able to judge, the question of encouraging and helping agriculture generally is engaging the attention of all the political parties. It is perfectly clear that the solution of the problem, so far as the farmer is concerned, is not simply the supplying of electrical energy. The guiding principle ought to be to secure the greatest economy of human effort, and I trust that the problem of greater efficiency in agriculture will not be obscured by any question of electrical development. With regard to the remarks of Mr. Fennell, I have always been under the curious misapprehension that the measure by which civilization advanced or is advancing could be correlated to the appreciation of the value of human life; and if, in order to provide cheap electrical energy on cheaply constructed open lines, those lines are going to take their toll of human life, well, all I can say is, frankly, that the electrification of farms does not appeal to me in the slightest. We have heard all about the sins of the Post Office—of course they are many—in protecting its plant, its operators, its subscribers and the members of the public, from the dangers caused by power circuits. Nobody appreciates more than I do the author's extremely valuable work in seeking to produce economy of human effort on the farms. He is right both theoretically and practically, but, after all, to supply electricity is merely to touch the fringe of the problem. The only opinion I venture to hazard is that it might be even more important that the small farmer should be in telephonic communication with the markets and the neighbouring farmers than that he should have a supply of electricity in bulk.

[The author's reply to this discussion will be published later.]

THE CAUSE AND ELIMINATION OF NIGHT ERRORS IN RADIO DIRECTION-FINDING.

By R. L. SMITH-ROSE, D.Sc., Ph.D., and R. H. BARFIELD, M.Sc., Associate Members.

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SUMMARY.

The paper describes experiments which have been carried out with a view to obtaining more conclusive evidence as to the causes of the apparent variations in bearings observed under certain conditions on wireless direction-finders. In the course of the experiments the Adcock "four-aerial" direction-finder has been developed, and with its aid it has been shown that the actual deviation in azimuth of wireless waves is practically negligible. These experiments thus constitute a proof that the variable errors observed on closed-coil direction-finders at night are caused by downcoming waves arriving from the upper atmosphere and polarized with the electric force in a horizontal plane. The investigation also indicates the possibility of the Adcock system being developed into a practical direction-finder which is free from night errors, and those errors associated with observations on aircraft transmissions made at a ground direction-finding station.

(1) OBJECT OF THE PRESENT PAPER.

The object of a large proportion of the investigations carried out by the present authors for the Radio Research Board during the past few years has been to ascertain definitely the cause of the apparent variations in bearings experienced on closed-coil direction-finding apparatus during the "night" periods. Some of these investigations have led to the development of methods of distinguishing between the electric and magnetic components of wireless waves, and of the separate measurement of their intensity and direction. This portion of the work has recently led to a definite proof of the existence of downcoming waves at the earth's surface with components of suitable polarization and sufficient intensity to account for a large proportion of the night errors experienced.*

In this manner the theory originally advanced by T. L. Eckersley † in 1921 to account for the apparent variations in the direction of arrival of wireless waves has been adequately confirmed; and it is now evident that these variations are caused by the action of the horizontal components of electric force in the downcoming waves on the horizontal parts of the direction-finding loops. A good discussion of these effects and the associated phenomena is given in Keen's book on the subject of wireless direction-finding.‡

It is generally assumed that the downcoming waves have travelled via the upper regions of the earth's atmosphere without deviating laterally from the great-circle plane through the transmitter and receiver. This assumption has, however, not been sufficiently well justified in the past; and the presence of the downcoming waves has hitherto made it difficult to prove whether the direct waves travelling along the earth's surface have not also suffered any lateral deviation. Another portion of the authors' investigations has therefore been made to ascertain to what extent, if any, such lateral deviation exists. The problem is one of more than pure scientific interest; for it is evident that, if directional receiving apparatus can be devised which shows the absence of lateral deviation, we are at once provided with a direction-finder which is free from the variable night errors that place such a serious limitation on closed-coil direction-finders. The present paper describes the experiments which have been carried out with these objects during the past 18 months.

(2) SUGGESTIONS AND ATTEMPTS BY PREVIOUS WORKERS.

The problem involves essentially the production of an apparatus which will measure the horizontal component of the direction of arrival of wireless waves, irrespective of their angle of incidence at the earth's surface or their state of polarization.

Three methods of attacking this problem have previously been described. In a patent filed in 1919, F. Adcock * described a direction-finding arrangement in which the aerials were mounted and connected in such a manner as to ensure that only the vertical parts were acted upon by the arriving waves. In this way he proposed to eliminate the errors which are caused by the effect of the horizontal electric field on the receiving system. This arrangement consisted essentially of four vertical aerials spaced at the corners of a square; the aerials at the extremities of a diagonal formed a pair and were connected in opposition to the field coils of a radiogoniometer. Provided that the horizontal members of the system have no effective E.M.F. induced in them, it is clear that the current in the field coils is due entirely to the phase difference of the E.M.F.'s induced by the vertical component of the electric force of the arriving waves. This current will thus depend only on the horizontal direction of arrival of the waves relative to the system.

In the paper already mentioned,† T. L. Eckersley

* R. L. SMITH-ROSE and R. H. BARFIELD: "An Investigation of Wireless Waves arriving from the Upper Atmosphere," *Proceedings of the Royal Society*, A, 1926, vol. 110, p. 580.

† T. L. ECKERSLEY: "The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, 1921, vol. 2, pp. 60 and 231.

‡ R. KEEN: "Direction and Position Finding by Wireless," 1922, p. 164.

* F. ADCOCK: "Improvement in Means for Determining the Direction of a Distant Source of Electromagnetic Radiation," British Patent 130490/1919.

† T. L. ECKERSLEY, loc. cit., p. 239.

suggested that any lateral deviation of wireless waves from the great-circle plane through transmitter and receiver could be measured by employing a receiver in which each of the ordinary closed loops of the Bellini-Tosi arrangement is replaced by two loops in the same plane connected together in series and so that their E.M.F.'s oppose each other. With such an arrangement the effective E.M.F. induced therein will be entirely due to the phase difference between the individual E.M.F.'s in the two loops resulting from their spacing. It is then evident that a wave arriving in a direction at right angles to the plane of the loops will produce no resultant E.M.F. in the circuit, whatever may be the angle of incidence or state of polarization of the arriving waves.

In 1921, G. M. Wright and S. B. Smith * published an account of experiments carried out with a direction-finder connected in such a manner as to give the heart-shaped polar diagram for reception. These experiments showed that, under conditions when large variations in apparent bearings were obtained on the ordinary direction-finder, the position of the heart-shape minimum remained constant although the actual shape of the polar reception curve altered considerably. The agreement of the experimental results with those predicted from Eckersley's theory served as a useful confirmation of this theory. The accuracy of such experiments, however, largely depends upon the purity of the minimum and, as Wright and Smith pointed out in their paper, the heart-shaped minimum only remains pure when the downcoming waves are arriving at a reasonably small angle to the horizontal (i.e. a large angle of incidence). In some of the authors' recent experiments, however, angles of incidence as small as 16° to the vertical have been measured,† and the behaviour of the heart-shaped diagram under such conditions is a matter for further investigation.

As far as the authors are aware, no account of the practical working of either of the above systems as direction-finders has yet been published, although the heart-shape circuit arrangement is now in common use for the determination of the "sense" of wireless bearings. Quite recently, however, a directional receiving system comprising two spaced loops mounted in a common vertical plane has been described by H. T. Friis.‡ This arrangement has been developed with a view to obtaining directional selectivity in ordinary wireless reception, and not as an application to direction-finding.

(3) Early Experiments at the Radio Research Board's Station, Slough.

(*a*) *Double loop method.*—In the first experiments, a modification of Eckersley's suggested method was employed. Instead of using two pairs of large double loops at right angles, a single pair of small loops was constructed and arranged in a vertical plane so as to be rotatable about a vertical axis.

The E.M.F. induced in such a system by a single wave is given by the expression :—

$$e = K \sin \frac{2\pi d \sin \theta}{\lambda} \cos \psi \, (\alpha \sin \psi + \beta \cos \psi) \quad . \quad (1)$$

where K is a constant for loops of a given area,
d = distance between the centres of the loops (assumed small compared with the wave-length λ),
ψ = angle between plane of loops and horizontal direction of waves,
θ = angle of incidence of the waves at the earth's surface,
α = horizontal component of magnetic field of waves in great-circle plane through transmitter and receiver,
β = horizontal component of magnetic field of wave perpendicular to α.

The above expression for the induced E.M.F. becomes zero when $\psi = 90°$, so that there is a zero or "minimum" position of the system when the plane of the coils is at

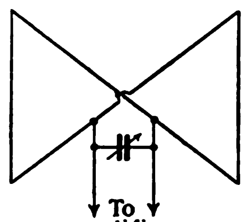

FIG. 1.

right angles to the horizontal direction of arrival of the waves, whatever may be their state of polarization or angle of incidence. It should be noted that this is not necessarily the only minimum which will be experienced in the rotation of the coil from 0° to 180°, since it is quite possible to have a second minimum at the value of ψ for which $\tan \psi = - \beta/\alpha$.

For simplicity of construction in the practical arrangement, the loops were made triangular in shape and consisted of a single winding in the form of a figure 8, as depicted in Fig. 1. These loops were erected in a hut which was suitably screened for the elimination of antenna effect, and the remainder of the receiving circuits and the amplifiers were adequately screened from the direct effects of the arriving waves. When the arrangement was tested it was found to work satisfactorily on near-by stations ; but owing to the fact that its reception factor is differential in nature, it was not sufficiently sensitive for operation on transmissions from the more distant stations. Hence it was not possible to use the apparatus under the conditions which give rise to the usual night phenomena in radio direction-finding. In the absence of a much more sensitive amplifier, the only methods of increasing the strength of the received signals would be either to increase the distance between the loops (d), or to adopt Eckersley's suggestion of employing large fixed loops on the Bellini-Tosi plan. In regard to the last alternative, it is seen from equation (1) that the E.M.F. is not propor-

* G. M. Wright and S. B. Smith : "The Heart-shaped Polar Diagram and its Behaviour under Night Variations," *Radio Review*, 1921, vol. 2, p. 394.
† R. L. Smith-Rose and R. H. Barfield, loc. cit., p. 612.
‡ H. T. Friis : "A New Directional Receiving System," *Proceedings of the Institute of Radio Engineers*, 1925 vol. 13, p. 685.

tional to cos ψ, and as the operation of the Bellini-Tosi radiogoniometer depends upon such a cosine law, this method cannot be adopted for the present case. Up to the present time no experiments have been made with loops separated by a greater distance, for, as will be seen below, the use of Adcock's method has been found to give more successful results.

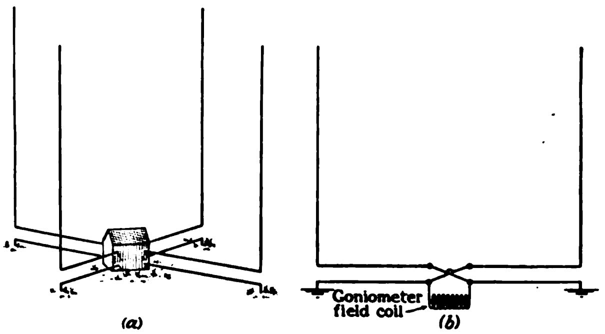

FIG. 2.

(a) Sketch of system. (b) Elevation of single pair of aerials.

(b) *Adcock's system.*—The simplest form which this system can take is probably that shown in Fig. 2 where each of the four aerials is earthed at a point vertically beneath it, but the earth lead is taken horizontally to the receiving hut at the centre of the system and back again. In Fig. 2 (b) only one pair of aerials is depicted to show the method of connecting the aerials in opposition through the field coil of the radiogoniometer. Such a mode of connection should have the effect of rendering any E.M.F.'s induced in the horizontal members of the system by the arriving waves equal and opposite with regard to the circuit "aerial-field-coil-earth," so that the net E.M.F. induced in this circuit is that due to the phase difference of the individual E.M.F.'s induced in the two vertical members. This E.M.F. is given by the equation

$$e = KZ\frac{2\pi d}{\lambda}\cos\psi \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where K is a constant for a given aerial system,

Z = vertical electric force,

d = distance between the aerials,

ψ = angle between direction of travel of the wave and the line joining the aerials.

Since the E.M.F. is proportional to cos ψ, it is clear that two pairs of such aerials may be used with a radiogoniometer in exactly the same manner that this instrument is used with the fixed loops of the Bellini-Tosi direction-finding system.

Experiments carried out with the above arrangement as in Fig. 2 showed that, due probably to stray capacities to earth, the horizontal E.M.F.'s induced in the system were not balanced out, and gave rise to serious errors.

(4) Attempted Improvement of Adcock's System.

With a view to overcoming the difficulty just mentioned, an attempt was next made to screen the whole of the horizontal portion of the system from the effects of the arriving waves. Previous experience had shown that in order to screen an aerial adequately, it was necessary for the screen to project beyond the aerial by a considerable length. The system finally adopted for the present case is depicted in Fig. 3, which shows one pair of aerials with the horizontal members contained within a screening trunk formed of a number of parallel wires. At their inner ends these wires were joined to the metallic lining of a screened hut which contained the whole of the receiving apparatus and the operator. Tests of the effectiveness of this screening arrangement were made by measuring the directional properties of the four individual aerials. These measurements unfortunately showed that the attempted screening of the horizontal portion of the aerials had been unsuccessful. The explanation of this result is probably that, whilst the screen effectively prevented any E.M.F. being induced directly in the horizontal members of the aerial system, the vertical component of the secondary electric field resulting from the currents in the screen itself, induced E.M.F.'s in the vertical portions of the

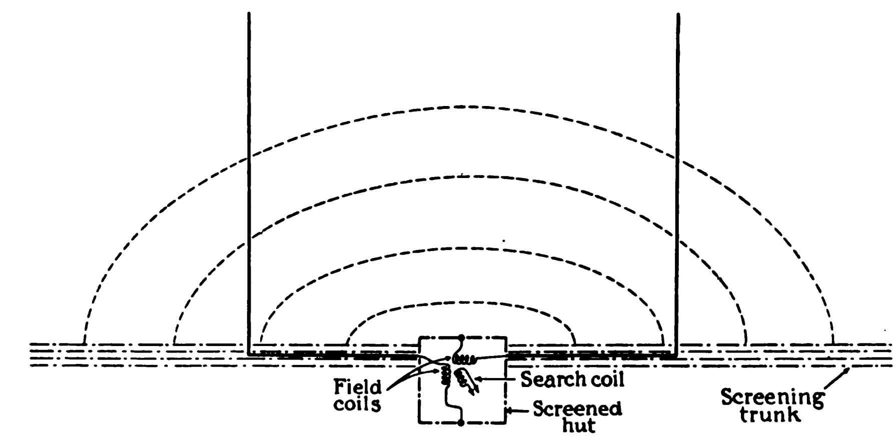

FIG. 3.

aerials (see Fig. 3). Since the currents in the screen are produced by the horizontal component of the electric force in the arriving wave, the condition that this component shall have no effect on the system is not fulfilled.

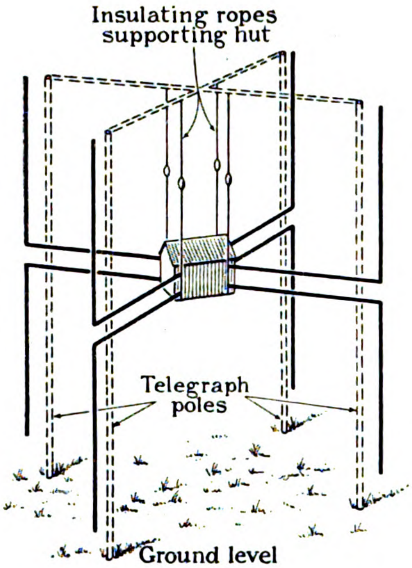

FIG. 4.

(5) FORM OF ADCOCK'S SYSTEM FINALLY ADOPTED.

It was now decided to revert to the alternative arrangement described by Adcock * in which the vertical aerials are comprised of complete Hertzian oscillators with leads taken horizontally from their mid-points to the receiving apparatus in the screened hut. In order

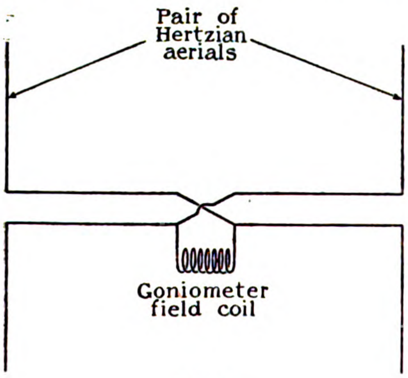

FIG. 5.

to maintain symmetry this of course necessitates the raising of the hut with the apparatus and operator to the level of the centre of the aerial system some 20 ft. above the ground. For the support of the aerial wires, four poles were available 44 ft. high, situated at the corners of a 20-ft. square. The receiving hut was placed at the centre of this system, being suspended by insulated steel ropes from cross beams attached to the poles, to reduce to a minimum its capacity to earth or to other structures.

* F. ADCOCK, loc. cit.

The arrangement is shown diagrammatically in Fig. 4, the circuit being as given in Fig. 5. By this reduction of the capacity to earth of the various parts of the system it was anticipated that the E.M.F.'s in the horizontal members would completely balance each other, and thus the system would be rendered free from the effects of any horizontal electric fields. The fulfilment of this condition was verified; first, by measuring the directional properties of the individual aerials as formerly; and secondly, by comparing the induced currents in the upper and lower halves of the same

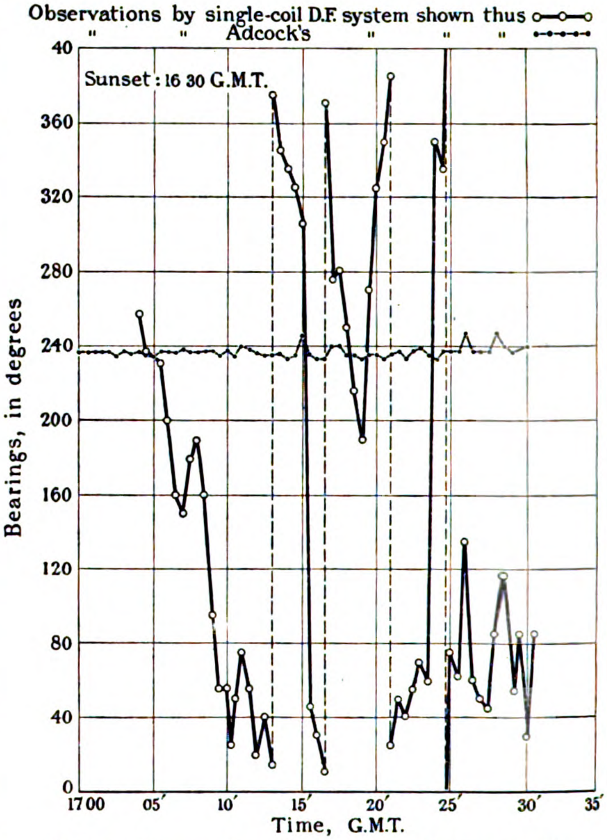

FIG. 6.—Observations of bearings on Bournemouth, 3 November, 1925 ($\lambda = 386$ m).

aerial. This last test brought to light a superiority of 2 or 3 per cent of the lower half over the upper half of each aerial, due probably to the difference in their capacities to earth. Although the error introduced by this asymmetry was very small, it could probably have been eliminated by suitably shortening the lower part of the aerial to make the two halves electrically equal. Since the whole method depends upon the assumption that the four receiving aerials are identical, it is important to observe that other tests showed that the receiving properties of the aerials was not materially influenced by slight differences or irregularities in the neighbouring supporting structures.

(6) CALIBRATION OF THE SYSTEM.

The apparatus was now calibrated for direction-finding by taking observations of the apparent bearings

of stations transmitting within the broadcasting band of wave-lengths, under conditions which gave freedom from night errors. In this manner it was found that the apparatus was subject to a permanent directional error of the same order as that experienced on the closed-coil direction-finders in use in the same field, due to the local surroundings.

(7) Determination of Lateral Deviation of Wireless Waves under Night Conditions.

In order to determine to what extent wireless waves can be laterally deviated from the great-circle plane connecting the transmitter and receiver, it was decided to make observations on some transmissions which were known to give rise to serious night variations on an ordinary direction-finder. Accordingly a series of tests was carried out in which the apparent bearing of a transmitting station was observed simultaneously on the above apparatus and on an ordinary single-coil direction-finder installed in another hut at about 100 yards' distance. In this manner observations were taken on the transmissions from Cardiff (353 m), London (365 m), Bournemouth (386 m), Newcastle (404 m), and Birmingham (475 m). The most serious night variations were obtained on Bournemouth and Cardiff, and Figs. 6 to 9 show graphically some of the results obtained in the simultaneous observations on these stations. Figs. 6 and 7 refer to the results obtained on Bournemouth on two different evenings; and these show very strikingly that the errors obtained on the Adcock system are almost negligible compared with those obtained on the single-coil direction-finder. Indeed, on several occasions, the latter system showed a rotation of the apparent bearing through more than 360°, whilst on the Adcock system the extreme variation in either of the tests was 14°. From the results on Cardiff plotted in Fig. 8 the same effect is observed, although the variations are less violent. On one occasion the bearing on the single-coil direction-finder rotated through 175°, whilst the extreme variation on the other system was about 7°. In the further observations on Cardiff plotted to a larger scale in Fig. 9, it is seen that when the normal direction-finding variation was comparatively small (14°) the extreme variation on the other set was 1°, which is of the same order as the limiting accuracy of the present apparatus.

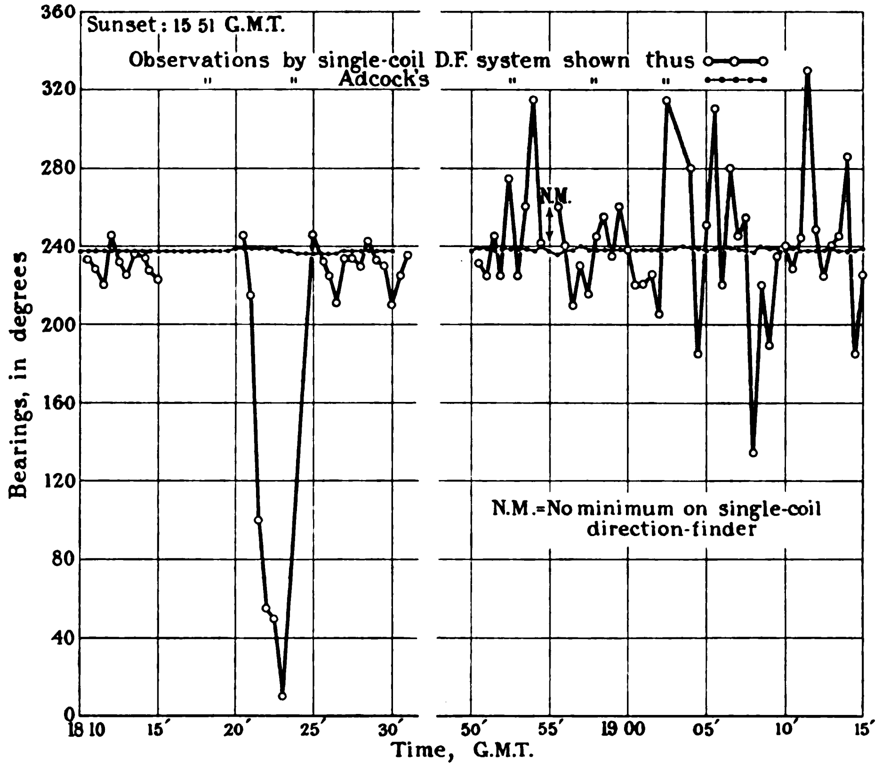

Fig. 7.—Observations of bearings on Bournemouth, 10 December, 1925 (λ = 386 m).

It is to be concluded from these results, therefore, that lateral deviation plays a negligible part in producing the large and variable errors in apparent bearings which are obtained at night on the present type of closed-coil direction-finding set; and that, therefore, these errors are entirely caused by the arrival of downcoming waves polarized with the electric force horizontal. We have, therefore, in this investigation a further proof of the existence of these downcoming waves which supplements and confirms those given in previous papers by Appleton and Barnett * and by the present authors.†

The slight residual variable errors noticed as having

* E. V. Appleton and M. A. F. Barnett: "On Some Direct Evidence for Downward Atmospheric Reflection of Electric Rays," *Proceedings of the Royal Society*, A, 1925, vol. 109, p. 621.

† R. L. Smith-Rose and R. H. Barfield, loc. cit.

been recorded on the "four aerial" system may, it will be seen, amount to $\pm$ 7°. These may be caused by a slight defect in the apparatus due to imperfect balancing by which the rotated downcoming wave is able to produce some slight current in the goniometer, or it may be actually a residual amount of lateral deviation. Before the point is settled by improvement of the apparatus it will be best to assume that it is due to the latter cause. The important point is, however, that

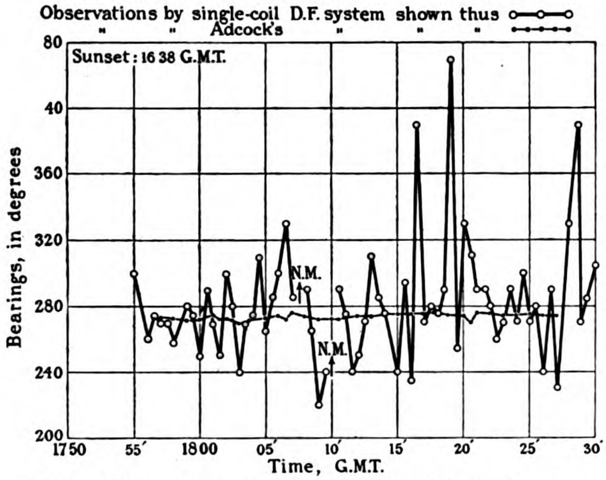

FIG. 8.—Observations of bearings on Cardiff, 26 January, 1926 ($\lambda = 353$ m).

even so, an error of $\pm$ 7° due to lateral deviation almost certainly does not imply that the waves are deviating to this extent from the great-circle path between transmitter and receiver, for it may be shown that, given two waves arriving with varying relative phase and with direction of travel in vertical planes separated by an angle ψ, the total maximum apparent variation in the resultant direction will greatly exceed ψ.* The conditions for this occurrence are simply that the two waves shall be approximately equal in amplitude and nearly 180° out of phase. It then appears extremely probable that the $\pm$ 7° apparent variation recorded is an indication of a much smaller real lateral deviation.

It may further be pointed out that a slight lateral difference in path between the horizontal and downcoming wave is almost certain to exist, for the horizontal wave on land is nearly always slightly deviated by local irregularities of the earth's surface (trees, etc.), whilst the downcoming wave on the other hand will not be influenced by these causes, at any rate to the same extent, and thus the two will probably not arrive exactly in the same vertical plane.

It is to be observed that, since there is no departure of the downcoming wave from the great-circle plane connecting tramsmitter and receiver, it is unlikely that the upper ionized layer, from which this wave is returned to the earth, is inclined to the horizontal. Such a tilt of the upper deflecting layer was suggested by Eckersley † as a possible cause of the downcoming wave having a

* See, for example, T. HEILIGTAG: "On the Causes of Error in Directional Reception," *Jahrbuch der drahtlosen Telegraphie und Telephonie*, 1923, vol. 21, p. 77.

† T. L. ECKERSLEY, loc. cit., p. 239.

component polarized with the electric force in the horizontal plane. Further, since it has previously been shown that directional errors are obtained on the transmissions from a vertical aerial,* it is evidently unnecessary for the horizontal electric force to be present in the radiation from the source. The investigations described in the present paper thus form a useful confirmation of the magneto-ionic theory of wave propagation which has been recently introduced by Appleton and Barnett † and by Nicholls and Schelleng,‡ in which the rotation of the plane of polarization of the downcoming waves is ascribed to the influence of

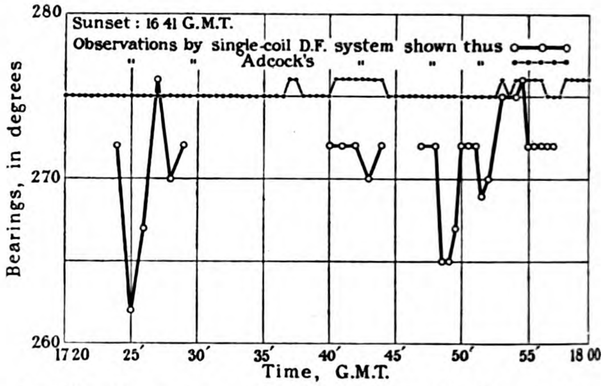

FIG. 9.—Observations of bearings on Cardiff, 28 January, 1926 ($\lambda = 353$ m).

the earth's magnetic field on the motions of the ions in the upper atmosphere.

(8) APPLICATION OF THE SYSTEM AS A DIRECTION-FINDER FREE FROM NIGHT ERRORS.

In the experiments described above it has been demonstrated that Adcock's four-aerial directional receiving system is successful in discriminating between laterally deviated waves and horizontally polarized downcoming waves. It is further shown that even during the times when the worst variations of bearings are obtained on the closed-loop direction-finding systems, the amount of actual lateral deviation of the arriving waves is very small. It therefore follows that such a system may be used as a direction-finder which gives the true direction of the great-circle plane of arrival of wireless waves whatever may be their state of polarization or their angle of incidence relative to the earth's surface. The system should, therefore, have important applications as an accurate direction-finder under night conditions, or for use in observing on aircraft at high angles of elevation, when the ordinary closed-loop direction-finder is subject to such large errors as to make it practically useless. For example, Baldus and Buchwald § have shown that the closed-coil direction-finder

* R. L. SMITH-ROSE: "The Effect of the Shape of the Transmitting Aerial upon Observed Bearings on a Radio Direction-finder," *Journal I.E.E.*, 1924, vol. 62, p. 957.

† E. V. APPLETON and M. A. F. BARNETT: "Wireless Wave Propagation," *Electrician*, 1925, vol. 94, p. 398.

‡ H. W. NICHOLLS and J. C. SCHELLENG: "Propagation of Electric Waves over the Earth," *Bell System Technical Journal*, 1925, vol. 4, p. 215.

§ R. BALDUS and E. BUCHWALD: "Experiments on the Wireless Orientation of Aeroplanes," *Jahrbuch der drahtlosen Telegraphie und Telephonie*, 1920, vol. 15, p. 214.

on the ground can give errors of as much as 60° in the bearings of aircraft.

In considering what will be the limiting accuracy of such a system it must be remembered that the variable error of $\pm 7°$ mentioned above was obtained under what are probably the worst conditions that can prevail in wireless direction-finding on medium wave-lengths. For it is worthy of note here that the variations of apparent bearing observed at Slough on the transmissions from Bournemouth are very much greater in both frequency and magnitude than any hitherto experienced by the authors during the past five years on all wave-lengths from 450 to 12 000 m. Under more favourable conditions, such as obtained in the case of the results taken on Cardiff, the maximum error experienced was only 2° or 3°, and it is considered that even this small amount can be reduced by a development of the system on a more favourable site. Also, on the longer wave-lengths allocated for commercial direction-finding the system will be subject to a still smaller error, and the instrumental difficulties will be somewhat decreased.

It is of course realized that in the practical development of the system it would be preferable to have the receiving apparatus, together with the operator, located on or near the ground and not at the centre of the aerial system as represented in Fig. 4. Several methods of overcoming the difficulties mentioned in Section 3 (*b*) have already occurred to the authors and these will be tested experimentally as soon as possible. A consideration of the case also shows that the system may be provided with the sense-finding modification, which is now a usual attachment to all direction-finders.

(9) Conclusion.

The experiments have shown that by paying careful attention to symmetry of construction, the system of direction-finding proposed by Adcock can be made to work with a considerable amount of success.

It has been employed as a means of discriminating between laterally deviated and horizontally polarized downcoming waves, demonstrating within the limits of experimental error that lateral deviation was non-existent and that, therefore, the latter type of wave was responsible, in all the cases examined, for the whole of the errors experienced at night in the closed-coil direction-finding system.

These experiments thus constitute an entirely self-contained proof that at night time there are waves arriving in a downward direction polarized with the electric force in a horizontal plane.

It has been shown that good reasons exist for the hope that this system may be successfully developed into a direction-finding system free from night errors and "aeroplane" effect.

These investigations were carried out for the Radio Research Board, established under the Department of Scientific and Industrial Research, and the authors desire to acknowledge their indebtedness to the Board for permission to publish the results. They also wish to thank Mr. R. Naismith for his assistance in the later portions of the experiments described in the paper.

APPENDIX.

Some Early Observations on Aircraft with the Four-Aerial Direction-finder.

By Frank Adcock, M.B.E., B.Sc.

It was suggested that as all the authors' observations were obtained on land transmitting stations it would be of interest for me to add an account of some experiments which were made with direction-finders on transmissions from aeroplanes in 1918. It was known at that time that bearings or directions obtained by means of the ordinary "closed loop" direction-finders were often quite inaccurate or indeterminable. Experiments with a Hertzian oscillator and with a small spark transmitting set fitted with two equal and symmetrically disposed aerials instead of the more usual aerial and earth arrangement confirmed the view that the vagaries of the ordinary direction-finders were due to the presence of a horizontal component in the electric force of the radiation emitted by an aeroplane in flight. Further, it was thought that this horizontal component

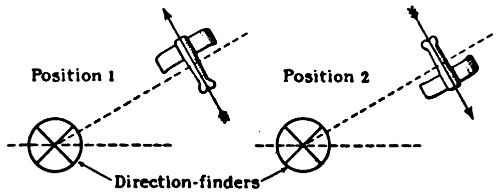

Fig. 10.

of the electric force of the radiation owed its existence to the two following independent causes :—

(1) An appreciable angle of incidence of the radiation in respect to the ground would cause the wave-front to lean forward.

(2) Owing to the drag of the aerial of an aeroplane in flight the axis of the "equivalent Hertzian oscillator" of the machine would depart considerably from the vertical. Under these conditions the horizontal electric component from this cause would be non-existent when the aeroplane was flying directly towards or away from the examination point, but would attain its maximum value when the machine was flying tangentially in respect to the observer.

The tests mentioned below were made with the aid of an aeroplane flying at a moderate altitude and at distances of 3 to 8 miles from the direction-finding installations, in which circumstances it was believed that any errors of direction would be associated almost entirely with the direction of flight of the machine. Two direction-finding installations were used for taking simultaneous observations on the aeroplane, one equipped with a revolving loop aerial, the other with the fixed experimental aerials devoid, as far as possible, of effective horizontal members. The two installations were erected close to one another but not so near as to cause

mutual interference. It was then arranged that the aeroplane fitted with a wireless transmitter should fly over a village in a direction at right angles to that of an imaginary line joining the village in question and the direction-finders. A return journey was then made over the same village, the aeroplane flying in the opposite direction. Wireless transmission took place when the machine was directly over the village, and the two positions of the aeroplane with respect to the direction-finders are shown in Fig. 10. The whole process was repeated over four villages situated at gradually increasing distances from the direction-finders, and the errors in the wireless bearings obtained in each case by both installations are indicated in the table above.

The results were meagre but it was clear that large and consistent errors were present in the bearings obtained with the revolving-loop direction-finder. On the other hand the apparatus fitted with the four vertical aerials gave errors in the bearings of only about one-fifth this magnitude. It was also of interest that the errors in the bearings taken with the revolving-loop direction-finder were reversed when the direction of flight of the transmitting aeroplane was reversed, and that these errors showed little tendency to diminish as the distance between the aeroplane and the direction-finder was increased.

TABLE.

Aeroplane flying over	Approximate distance of aeroplane from both direction-finders	Approximate true bearing of aeroplane from both direction-finders	Erorr of bearing on aeroplane as recorded by direction-finder with revolving-loop aerial		Error of bearing on aeroplane as recorded by direction-finder with four vertical aerials	
			Aeroplane in position No. 1 (Fig. 10)	Aeroplane in position No. 2 (Fig. 10)	Aeroplane in position No. 1 (Fig. 10)	Aeroplane in position No. 2 (Fig. 10)
	miles					
Village A	3	65°	—	− 21°	—	+ 1°
Village B	4	67°	+ 24°	− 33°	− 1°	− 6°
Village C	5½	66°	+ 31°	− 23°	− 3°	− 5°
Village D	8	63°	+ 40°	—	− 2°	+ 1°

The authors have made a very comprehensive examination of the wireless radiation from land stations under various conditions and if they can be induced to extend their investigations to a thorough examination of the radiations emitted from elevated sources, the publication of my own scanty observations will be justified.

DISCUSSION BEFORE THE WIRELESS SECTION, 5 MAY, 1926.

Mr. R. H. Barfield: I should like to point out one or two details which have occurred to Dr. Smith-Rose and myself since we wrote the paper, and also, perhaps, to forestall one or two of the more obvious criticisms to which the paper might otherwise be subjected. In the first place the system clearly has an application as an ordinary directional receiver, i.e. one in which its directional properties are made use of to minimize interference. Most of the established methods of directional reception work on the assumption that the waves are vertically polarized and they therefore break down when this is not the case. The present system has not this disadvantage and should therefore be an improvement as a method of reducing jamming or atmospherics at a receiver. For we now know that signal waves may often be circularly polarized and it is at least highly probable that atmospherics sometimes also are. There is certainly no evidence to the contrary. A criticism might well be raised that the Adcock direction-finding system could not possibly be worked in practical circumstances owing to the delicacy of the balancing required which might be upset by the presence of surrounding objects. Now for the successful working of the new system much the same conditions are required as for any other direction-finder. The two essentials are: (1) That the instrument shall be designed correctly to work in accordance with its theory, and (2) that a minimum space shall be provided round the system free from all conductors and of homogeneous or symmetrical dielectric properties, or, failing this, one in which all the electric properties remain constant. As regards the first of these I think we may now claim to have satisfactorily solved the problem of design. For the second, the dimensions of the minimum space will probably vary with the wave-length and the point remains to be investigated. So far, however, there is no evidence that the Adcock system requires any more space than any other direction-finding system; nor does there seem to be any particular reason why it should. In connection with the space occupied by the system, it has probably occurred to some that the arrangement we have described is not the most fundamental form which the system can take. The simplest arrangement would consist of a single pair of opposed aerials mounted rigidly on an arm so as to rotate about a vertical axis (see Fig. A), and which would take the form of a metal pipe down which the leads would be brought to a screened box on the ground. The circuit

diagram would be much the same as with the four-aerial system (Fig. B). The tuned circuit and the amplifier would be contained in a screened box forming the base of the apparatus. The advantage of this arrangement is that it might be made much smaller than the four-aerial system, to which it bears exactly the same relation as the closed-coil direction-finder bears to the Bellini-Tosi system. There does not seem to be any doubt that such a system as this will work satisfactorily, but we have not yet had time to try it. Returning finally to the four-aerial system, since the total signal strength obtained is the result of the small differential action of two identical aerials connected in opposition, and, further, since the aerials are not even directly tuned and are of dimensions too small to be efficient except for very short waves, it might well be questioned whether the apparatus had not attained its perfect directional properties by making too great a sacrifice of its range of working. As a matter of fact this is not at all the case. The daytime range obtained with the apparatus just described is over 200 miles to a standard B.B.C. station, but this is far from being a maximum range. This apparatus was not constructed from this point of view at all; not only could its aerial system be greatly

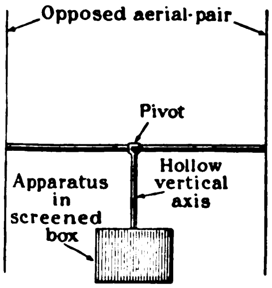

FIG. A.

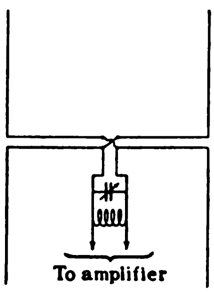

FIG. B.

improved in efficiency if necessary, but by the use of modern amplifying apparatus alone the range could without doubt be greatly increased. Thus the question of the range of the Adcock system in comparison with that of other systems is not likely to arise.

Admiral of the Fleet Sir H. B. Jackson: I should like to congratulate the authors on the results they have obtained after many years of labour in getting a directional system which may be free from night errors. I hope that they will be able to make of it a practical working instrument suitable for replacing the present Bellini-Tosi ones in places where they are erected. The Radio Research Board agrees with the results of these experiments. What the effect would be on the coil system on board ships it is difficult to foresee, but I think that if the night errors can be reduced to nil—they are not very great at present on the distances used at sea, it is true—it will be a great improvement and enable reliable bearings to be obtained at night at much greater distances than at present.

Mr. R. Keen: Although the paper is very interesting, I read it with mixed feelings. The authors make reference to the work of previous adherents to the Eckersley theory, but they fail, I think, to make clear that much of the confirmation which they bring forward had been produced in almost identical form by these earlier writers. Under the heading "Objects of the present paper" the authors say: "This portion of the work has recently led to a definite proof of the existence of downcoming waves at the earth's surface with components of suitable polarization and sufficient intensity to account for a large proportion of the night errors experienced." With regard to this, I think that Eckersley, in his original article in the *Radio Review* * gave very good proofs that the errors were caused by these downcoming waves with abnormal polarization, and, in addition, the article by Wright and Smith, to which the authors refer, afforded a number of examples of the 360° rotation of bearings similar to those now shown in connection with Bournemouth. In 1920 Wright and Smith were taking bearings at Chelmsford on Clifden which at that time was working on 6 000 m (C.W.) and also on Lyons on a 5 000-m arc transmission. One of the Clifden error curves shows that there was a tendency for the rotation to occur at intervals of approximately 20 minutes and this was the period which would be expected to elapse between two cycles of interference between the direct and reflected waves as the Heaviside layer was rising. The Bournemouth rotations on a much shorter wave-length appear to be at 4-minute intervals. Another instance of 360° errors is referred to briefly in my book † when dealing with the confirmation of the Eckersley theory. When the Marconi Co. originally started their wireless service to Paris, reception at this end was carried out on a Bellini-Tosi aerial with a figure-of-eight diagram, the wave-length being 2 300 m. Before the heart-shaped diagram was substituted for the figure-of-eight, complete rotations of the bearing of Paris were not unusual near the time of sunset, and on one evening in 1921 the apparent bearing of Paris made 3½ complete rotations within an interval of 15 minutes. On the assumption that these rotations are due to interference between the direct and reflected rays, then at the instant of maximum error there should be a drop in signal strength since the direct ray and the normally polarized component of the reflected ray are in phase opposition. Signal-strength measurements were accordingly made on Clifden by Wright and Smith, and the intensity was found to fall as the error increased, and in certain cases dropped almost to zero at the instant of 90° error. I do not wish to appear too critical, but I think it right to emphasize that these 360° rotations of bearing were well known 4 years ago, and I consider it hardly correct for the authors to say that "it is now evident that these variations are caused by the action of the horizontal components of electrical force in the downcoming waves," etc.; because many of us were convinced of this after the previous work on the subject was published. The results obtained with the Adcock aerial system are extraordinarily interesting, and the graph of Fig. 6 must surely be the first to be published showing such a complete conquest of night variations. If the system can be put into a more practical form, whilst retaining its accuracy, it should be of great commercial value. The Marconi Co. made

* T. L. ECKERSLEY: "The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, 1921, vol. 2, pp. 60 and 231.
† R. KEEN: "Direction and Position Finding by Wireless," 1922, p. 164.

some tests on the Adcock system some years ago using the arrangement shown in Fig. 2, but wave-lengths of several thousand metres were used. This made the whole operation rather more difficult, although trouble with the screening cage disappeared since underground cables could be used. The work had to be abandoned before any success was achieved approaching that now recorded by the authors. It would be interesting to know whether a capacity radiogoniometer has been tried in place of the inductive one. Since open aerials are being used, there might possibly be some advantage in doing so. Mr. Barfield has mentioned the use of the Adcock system for directional reception, as by its means a heart-shape minimum can be maintained under the worst night-effect conditions. It should certainly be very useful in this connection, but at the same time it is an uncommon thing in this country for the down-coming ray, on wave-lengths between 2 000 and 20 000 m, to be so steep as to upset the normal closed-coil heart-shape balance. At the Marconi receiving station at Brentwood there are 14 receivers employing heart-shape reception and it is only rarely necessary to alter adjustments due to this cause, although at some Continental stations where the district is mountainous a certain amount of trouble is experienced at sunset in maintaining the minimum for the elimination of jamming. It is mentioned on page 836 that: " The investigations . . . form a useful confirmation of the magneto-ionic theory of wave propagation which has recently been introduced by Appleton and Barnett and by Nicholls and Schelleng, in which the rotation of the plane of polarization of the downcoming waves is ascribed to the influence of the earth's magnetic field on the motions of the ions in the upper atmosphere." I think, however, that some credit for this should be given to Dr. Eccles who, in his Inaugural Address * to the Wireless Section in 1921, said that the action of the earth's field on free electrons in space would account for the rotation of the plane of polarization to this extent. I am glad that the authors have now experienced some of these violent variations on C.W. signals, because they will appreciate why it was that in discussions on their previous papers on night variations I have always insisted that errors were greater on C.W. than on spark. Having seen, on various occasions, the apparent bearing of a station move through 360°, makes one prejudiced against long-distance C.W. bearings with a closed-coil direction-finder. Lest this paper should, however, give the impression that all direction-finding is unreliable, it must be remembered that the authors were deliberately searching for bad night effect and that it has been proved by their previous tests that, up to 100 miles over sea, either spark or I.C.W. transmission will give all the reliability required for the navigation of ships.

Mr. J. M. Furnival: The authors refer to inaccuracies of bearings received by ground direction-finding stations from aircraft in flight. The tests mentioned in the Appendix were made with the aid of an aeroplane flying at a moderate altitude and at distances of 3 to 8 miles from the direction-finding installation. The tabulated data would appear to indicate considerable errors observed on a revolving-loop direction-finder, and it is furthermore stated that these errors showed little tendency to diminish as the distance between the aeroplane and the direction-finder was increased. It may be of interest to compare the results thus obtained experimentally under the conditions described with those achieved by the Bellini-Tosi ground direction-finding stations which have been in operation for the past 4 or 5 years in connection with the navigation of civil aircraft on the cross-Channel air routes. It may be explained that Bellini-Tosi direction-finding stations have been established for this purpose by the Air Ministry at Croydon, at Pulham in Norfolk, and lately at Lympne in Kent. Similar stations have also been arranged at various important air stations in Europe. The results of several years' experience show very definitely that during daylight hours an accuracy of within $1\frac{1}{2}°$ can be normally expected. Due to the speed of approach of the aircraft, which in any case makes the passing of bearings at close ranges an operation of some difficulty, any errors which may exist when the aeroplane is in close proximity to the station have not in practice been detrimental to the service to any appreciable extent. The great value of this service to aerial navigation is now well established, and this is borne out by the experience gained by pilots both in practice and also when flying in conditions of bad visibility. [The speaker here quoted extracts from numerous reports, by permission of the Air Ministry.]

Mr. F. Adcock: I am rather out of touch with " wireless " as applied to aircraft at the present time, and it is possible that a modern aeroplane carries a fairly heavy weight on its aerial, in which case the angle taken up by the aerial when unwound may be nearly vertical. That would have the effect of bringing the bearings much nearer the truth. In the actual tests that were made, we set out to obtain the largest possible errors (with the ordinary direction-finders) and the experiments were carried out in 1918 with that object in view. We did not use the Bellini-Tosi but the revolving-loop system. I take it that the Bellini-Tosi apparatus should be subject to similar errors.

Mr. E. H. Shaughnessy: Judging from the curves shown, although the Adcock direction-finder does vary, it does not seem to vary in the same way as the coil. Where there is a maximum deviation in the coil in one direction, the curve for the Adcock aerial seems to bend in the opposite direction. This seems to be common to all the curves. Is there any reason for this? The phenomenon can be clearly seen in Fig. 8 just after 18 20 G.M.T. and at 18 05 G.M.T. I take it that an error of 7° on a direction-finder is almost as bad as one of 50°. It seems, therefore, that unless the error can be reduced to, say, not more than 2°, the bearing cannot be relied upon and that the system is no better than the Bellini-Tosi. With regard to the day error, our practice with the Bellini-Tosi system shows we can get quite good results within 2°. Moreover, when we get these installations at shore stations calibrated by means of the ships the navigating officers say that they cannot get nearer than 2° in their calculation unless they have objects on land on which to take sights, which indicates that there is little to choose between compass bearings and wireless directional bearings.

* *Journal I.E.E.*, 1921, vol. 59, p. 83.

Lieut.-Col. H. P. T. Lefroy: The authors have not mentioned the subject of fading. If fading can be reduced by using the Adcock aerial, it might become a valuable form to use for broadcast reception. Referring to Fig. 5, would it be possible to get any compensation for asymmetry by sliding the connections of the lower antenna, leaving the upper connections fixed on the ends of the goniometer coil ?

Prof. J. T. MacGregor-Morris: Why does the bearing of the Bournemouth station show such excessive variations as compared with other stations which have been tested ? One speaker in the discussion has mentioned that it is not only a question of rather limited changes of wave-length, because he gave an example of a wave-length of 6 000 m where there was a revolution of this kind. Referring to Fig. 6, apparently the direction from which the received wave has come has undergone two complete revolutions and then has turned back through the same number of revolutions, as if it had to uncoil itself. Is this borne out by other observations ? The variations of bearing shown in this figure are very striking. They are taken, I understand, on the direction in which the waves appear to come from Bournemouth at Slough. If simultaneous observations were taken at Bournemouth when Slough was radiating, would the converse hold good ?

Major B. Binyon: I am very interested in what Mr. Barfield said with regard to future developments, because it seemed to me he was very confident on the sensitivity question. I should like to ask him if satisfactory signals could be received on an Adcock direction-finder having aerials of approximately the size of coil direction-finders as now used for ships. With regard to the disturbing effect of stray capacities in the original arrangement as shown in Fig. 2, in that sketch the two parallel horizontal leads are shown very far, apart; this may be only a matter of draughtsmanship, but it seems to me that the distance between the leads could be made absolutely negligible in comparison with their distance from the ground. This should reduce the asymmetry produced by capacity to earth. I presume that the $\pm$ 7° errors in bearings on Bournemouth, etc., were taken with the Hertzian oscillator apparatus. What would be the magnitude of the errors if the arrangement shown in Fig. 2 were used; would the horizontal effect be much worse ?

Dr. S. H. Long (*communicated*): I should first like to emphasize the valuable scientific contribution by the authors to the vexed question of the reflected polarized down ray and its resultant effect of producing "night-effect" errors in direction-finding work. The apparatus as designed and described certainly appears to offer immense possibilities for employment in cases where suitable care can be taken to ensure its being erected on a most favourable site where ample space and other facilities are available. It would then be of great importance to the safety of aerial and marine navigation, and it is for those purposes, I consider, that it appears to be specially adapted. I feel, however, that one should not overlook the present tendency in marine wireless direction-finding to install the apparatus on the ship rather than on the shore, and the ever-increasing number of radio beacon stations seems likely to encourage that tendency in the future. Now on board ship the conditions are very different from those on land. The apparatus has to be installed in a situation which is convenient to the general working of the vessel and which has in the majority of cases not been in any way selected for efficient wireless direction-finding. Further, the mere presence of the metal mass of the ship is an influence which may give results comparing unfavourably with those described by the authors. The space available for the installation is invariably limited, especially on cargo vessels where interference must not be caused to the working of cranes and cargo hoists. In the past it has been an unfortunate practice of navigators to demand a direction-finding bearing when night effect has been present and the wireless operator has taken, if minima were possible, one or two bearings and either cancelled them or sent them to the bridge marked "night-effect." Naturally in a large number of cases these results have caused wireless direction-finding apparatus to be regarded as unreliable for navigation purposes. Experience, however, shows that if a direction-finding set is designed to indicate the actual presence of night-effect, and the operator does not take one but a large number of bearings over a period of 5 mins., then the mean bearing is sufficiently accurate to be a valuable aid to navigation. The usual procedure now adopted when night-effect is present, on one large liner employing a single-coil direction-finding set with suitable compensating devices when making New York, is for the operator to submit a list of bearings on Nantucket at each sending period. All these bearings are submitted to the navigator, who can obtain a large degree of accuracy from the mean bearings. The following example is that obtained on such a liner when night effect was so bad that the shore station refused to give a bearing.

Time, G.M.T.	Maximum	Mean bearing	Difference against visual checks
15 20	272°	267·5°	+ 0·5
15 25	263°		
	272°	267·5°	+ 0·5
	263°		
15 30	272°		
	262°	267°	$\pm$ 0·0

Thus, in practice, provided bearings over a period of 5 mins. can be taken—and this is nearly always possible on direction-finding beacon stations—the "night-effect" does not become a really definite drawback. It is, of course, essential that both wireless operators and navigators should fully understand the problem. When examining Fig. 6 it appears at first glance that the night-effect difficulty with regard to the use of the direction-finder as an aid to marine navigation has been overcome, but on closer consideration it appears that there is a residual amount of lateral deviation which may amount to $\pm$ 7°. It seems doubtful whether, as

a point of practical navigation, it would not be preferable to continue to employ a direction-finder suitably designed so that unreliable bearings could be immediately recognized as unreliable, rather than a direction-finder which gives a definite reading which may or may not be subject to a deviation of $\pm 7°$ from the apparent bearing. I should like to ask the authors how the bearings given in the paper were actually taken. If they were taken on the carrier wave, by what method was the oscillator introduced into the single-frame and the Adcock systems? Moreover, what was the "arc of swing" in obtaining the bearings? With the increasing number of C.W. installations, and the desirability of obtaining accuracy on C.W. stations, I should think that the interaction of 5 frames as used by the authors (i.e. 2 main aerials, 2 field coils and 1 search coil) would render the system somewhat difficult to design for the accurate taking of C.W. bearings. Moreover, in "sense" determination—and this is essential in all modern direction-finding work—the phasing of the waves in the frame systems must be exceedingly complicated, and, as the whole sharp determination of "sense" is dependent on the accurate balancing of phasing in the systems, this problem does not appear capable of a simple solution such as can be obtained by the single-frame system.

Dr. R. L. Smith-Rose and **Mr. R. H. Barfield** (*in reply*): Mr. Keen has taken us to task for presuming to claim priority in the matter of the proof that night errors in direction-finding are due to the arrival of downcoming waves horizontally polarized. We would reply, however, that no such claim was intended. Full references are given in the paper to the work of all those mentioned by Mr. Keen, and, whilst we fully recognize the value of such work, others besides ourselves have considered that further confirmation was necessary. As a result of the research for such confirmation we think it will be agreed that our knowledge of the influence of the upper atmosphere on wireless transmission has been very materially enhanced. We must further emphasize that the present paper contains the first proof that wireless waves travelling around the earth, whether directly or via the upper atmosphere, suffer no appreciable lateral deviation from great-circle planes, a possibility to which attention was drawn in Mr. T. L. Eckersley's paper.* In final defence we would also remind Mr. Keen that there are still individuals, both within and outside this country, who are sceptical about the Heaviside layer.

On the question of the complete rotation through 360° of a signal minimum on a direction-finder, the following quotation may be given from a report † on an investigation on the variations of bearings of transmitting stations, both spark and continuous wave, operating at various distances on wave-lengths between 2 000 and 12 000 m. "The largest error recorded during the whole two years' observations was over 105°, but errors of this magnitude were extremely rare, and out of the 164 000 observations tabulated only in three cases was an error exceeding 90° experienced." In a later report * dealing with the continuation of the investigation on wave-lengths down to 450 m it was stated that "the maximum observed error on any station was 82·7°." This experience conflicts somewhat with that mentioned by Mr. Keen, and we must repeat that we still consider a rotation of bearing of more than 90° an exceptional occurrence. Even now we have only experienced a rotation of 360° in the case of Bournemouth's transmissions received at Slough, although observations have been made on several other of the British Broadcasting Co.'s stations on neighbouring wave-lengths. The condition for such rotations is evidently a critical one and depends upon getting the wave-length, the relative intensities of the direct and downcoming waves, and the polarization and angle of incidence of the latter, all of the right order. Owing to the fact that observations under identical conditions have not been made on damped-wave transmissions, we cannot agree with Mr. Keen that these results in any way affect the question of the relation between wave-damping and directional errors. All these points, however, would appear to be somewhat irrelevant to the main object of the paper, which, as Mr. Keen appreciates, has been to demonstrate the utility of the Adcock system in overcoming night errors in radio direction-finding.

From Mr. Furnival's remarks we gather that the only difficulty experienced in practice in the operation of ground direction-finding stations for observing the bearings of aircraft is in the matter of night errors. This would therefore seem to be a good case for the application of the Adcock system, which has the additional advantage that, *if necessary*, it can be used for accurate bearing observations at short ranges.

We think that the coincidence between the maximum deviations in opposite directions on the single coil and Adcock systems pointed out by Mr. Shaughnessy is accidental, for it does not always occur in the diagrams given in the paper (cf. Fig. 6 at 17 25–17 30). We do not consider that an error of 7° is quite as bad as one of 50°, but there seems to be every hope that the error of the Adcock system may be reduced to 2°, which is quite adequate for most navigation purposes at the present time.

In reply to Lieut.-Col. Lefroy, the fading of signals received on the Adcock aerial system should be of the same order as that experienced on any vertical aerial, since in both cases it is due to the variation in the intensity of the vertical electric force in the arriving waves. Since the Adcock system does not receive waves polarized with the electric force horizontal, the fading effects may not be quite the same as those experienced with an inverted L or a T aerial, but it is doubtful if any material advantage for broadcast reception is to be gained in this manner.

On the subject of the excessive variations in the bearings of the Bournemouth station, we would refer Prof. MacGregor-Morris to our reply to Mr. Keen above. The curious behaviour of the variations noted in Fig. 6 has not been confirmed by other observations. We regret that we have at present no data that will

* *Radio Review*, 1921, vol. 2, p. 239.

† R. L. Smith-Rose: "Variations of Apparent Bearings of Radio Transmitting Stations," Part II, Radio Research Board Special Report No. 3, 1925, p. 103.

* R. L. Smith-Rose: "Variations of Apparent Bearings of Radio Transmitting Stations," Part III, Radio Research Board Special Report No. 4, 1926, p. 48.

enable us to answer the question as to the reciprocity of transmission between Bournemouth and Slough.

Major Binyon is correct in assuming that the horizontal leads in Fig. 2 are shown well separated for the purpose of clarity. In practice these leads should be as close together as is compatible with a small capacity between them. Having established the validity of the principles underlying the Adcock system and the fact that the lateral deviation of wireless waves is negligible, with the aid of apparatus represented diagrammatically in Figs. 4 and 5, we are now returning to the arrangement depicted in Fig. 2 with a view to removing the defects formerly experienced in its practical operation. While it may be difficult to reduce the dimensions of the system to that of a small frame coil, we see no reason why future development should not result in an Adcock direction-finder of suitable size for installation on board ship, and with adequate range for navigation purposes.

In reply to Dr. Long it would appear that on any direction-finding system which is subject to variable night errors the existence of these errors can be detected by taking successive observations over the space of several minutes. We agree entirely that the effect of a night error can be considerably reduced by taking the mean of such observations. On the medium wave-lengths employed for navigation purposes a period of 5 to 10 minutes will probably be sufficient for such a series of readings, but on the longer wave-lengths of from 2 000 to 20 000 m a night error may remain comparatively constant for $\frac{1}{2}$ hour at a time. It has been consistently pointed out, however, in previous publications * that over long periods the mean bearing at night is seldom more than 1° or 2° in error, although individual observations may be subject to errors up to 60°. Considering that the experiments described in the paper constitute the first systematic test of the Adcock system, we feel justified in assuming that an extreme error of 7° under the worst conditions for direction-finding is an extremely favourable beginning; and we feel confident that the system will in due course play its part in the application of direction-finding to navigation. All the bearings recorded in the paper were observed on the carrier wave of the broadcasting station concerned, a beat note being obtained by introducing oscillations from a local source. This source is adequately screened in a manner previously described.† A standard form of such screened oscillator has now been in use for continuous-wave direction-finding for several years and it has given every satisfaction for this purpose. We can assure Dr. Long that, provided correct precautions are taken with the apparatus by applying now well-known principles, there is no reason why direction-finding on continuous waves should not be quite as accurate as with damped waves (spark or interrupted continuous waves). Mr. Barfield has already drawn attention in this discussion to the possibility of the Adcock system being made quite as simple as the single-frame system, and this is one of the lines which future development will take.

* R. L. Smith-Rose: "Variations of Apparent Bearings of Radio Transmitting Stations," Radio Research Board Special Report No. 2, 1924; No. 3, 1925; No. 4, 1926.

† R. L. Smith-Rose: "On the Electromagnetic Screening of a Triode Oscillator," *Proceedings of the Physical Society of London*, 1922, vol. 34, p. 127.

THE ECONOMICS OF LAMP CHOICE.*

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SUMMARY.

Lamps are first compared with other electrical apparatus as regards the possibility and the method of economic choice. Choice of type (carbon, metallic vacuum and gas-filled) is first considered, and then choice of rating for a given type, the latter being treated both graphically and algebraically. Simple formulæ are developed for the most economical rating, first with a fixed lamp and then with a fixed candle-power. These are applied to a number of different cases, and various courses of action are suggested for the manufacturer and the lamp user.

TABLE OF CONTENTS.

(1) INTRODUCTION.

In an earlier paper † it was pointed out that in dealing with any piece of apparatus or equipment in which a greater first cost would result in decreased running costs, the size of such apparatus can be determined in either of two ways, physical or economic. That is to say, the size may be the minimum required to perform the given service without risk of breakdown or damage, or it may be that size which will give minimum total costs over a number of years of service. With most apparatus it is the former which receives chief consideration, but with lamps the economic criteria are always the determining factor. Physical limits, such as the actual burning out of the filament, are never reached, and the working current is limited, not by the fear of immediate fusion, but with regard to length of life.

The rating of an incandescent lamp is therefore chosen on purely economic grounds, since any desired efficiency can be obtained by suitably over- or under-running, and the efficiency normally quoted is merely that which the lamp will attain when so run as to have a certain average length of life. This point of running, with the consequent length of life, is fixed by the lamp makers, usually at such a point that the lamps will have an average life of about 1 000 hours, but strictly it should vary according to the particular situation. For if energy is expensive it will clearly pay the consumer to over-run his lamps, getting a shorter life at a higher efficiency, and vice versa.

Lamps differ in two important respects from most other electrical apparatus. In the first place the life is reckoned in hours of burning rather than in hours of actual existence, i.e. the lamp is presumed not to depreciate except with use, and (barring mechanical vibration or long periods of idleness) this assumption is probably sufficiently accurate for the purpose. In the second place, lamp renewals are relatively so frequent that the interest charges can be neglected in comparison with the depreciation charges.* This obviates the difficulty of having to summate replacement charges dependent upon hours of burning, and interest charges dependent upon calendar hours.

Thus the economic calculations in connection with illumination are made on a basis of a service unit, e.g. lumen-hours, whereas most other economic comparisons are made on the basis of a time unit, e.g. annual costs or total capitalized costs.

(2) ECONOMIC CHOICE OF TYPE.

The problems which occur can be considered under two headings :—

(i) Choice of Type (usually between two or three alternatives).
(ii) Choice of Rating, i.e. voltage, and therefore efficiency (over a range of alternatives).

As an example of the former type of problem it will be sufficient to take a single case in which illumination is required in units having a mean horizontal candle-power of approximately 32 off a 220-volt circuit. It may be supposed that for this service there are available a 32-c.p. carbon lamp taking 110 watts and costing 1s. 9d., a 40-watt vacuum metal-filament lamp costing 2s. 6d., and a more efficient metal lamp, either vacuum or gas-filled, rated at 30 watts and costing 3s. 6d.† It is further assumed that they all give the same candle-power and that there is no qualitative difference between them for the purpose required.

Dividing the difference in price by the difference in watts, it will be seen that as between the carbon and the metal-filament vacuum lamp, energy will have to be less than 9d./70 = $\frac{1}{8}$d. per unit for the carbon lamp to be cheaper; whilst as between the two metal

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1926, vol. 64, p. 337.

* A single example will show this. A lamp which is burning for 3 hours a night and lasts 1 000 hours has to be renewed approximately once a year. With interest at 5 per cent the interest charge would be 1/20th of the depreciation or renewal charge, and can therefore be neglected in comparison.

† These figures are purely for illustration purposes to meet the case in which several makes or types of lamp are available for the same service, having different prices and corresponding efficiencies. On the larger sizes this often arises between the vacuum and the gas-filled types, but for the size mentioned the gas-filled lamp has little or no advantage.

lamps, energy will have to be more than 12/10 = 1·2d. per unit for the more efficient one to be cheaper. For any energy price between these two, the metal-filament vacuum lamp is the least expensive to employ.

The comparison would of course be more favourable to the carbon lamp if smaller lighting units were required, but however cheap the energy it is doubtful whether the carbon lamp would compete with a metal-filament lamp under-run in the manner described below, except under special circumstances such as severe vibration or extremely intermittent use.

(3) Choice of Rating (Graphical Treatment).

In considering problems concerned with the choice of rating over a range of alternatives, it is necessary first to fix on a criterion of rating. When a lamp which is intended by the makers to be used on a certain pressure is run on a different pressure, say a higher one, it may be said to be over-run, with results that can be summarized as (1) higher pressure, (2) higher efficiency, (3) higher candle-power, (4) lower life. The degree of over-running can therefore be expressed in the terms of the change in any one of these four quantities, and as the percentage efficiency change is very roughly twice the percentage pressure change, it will be convenient to define the degree of over- or under-running from the change either in efficiency or in applied pressure.

In what follows it will be best first to take a single instance, treating it graphically and approximately, before working out the more general case by an algebraic means, and for this purpose the following data will be employed :—

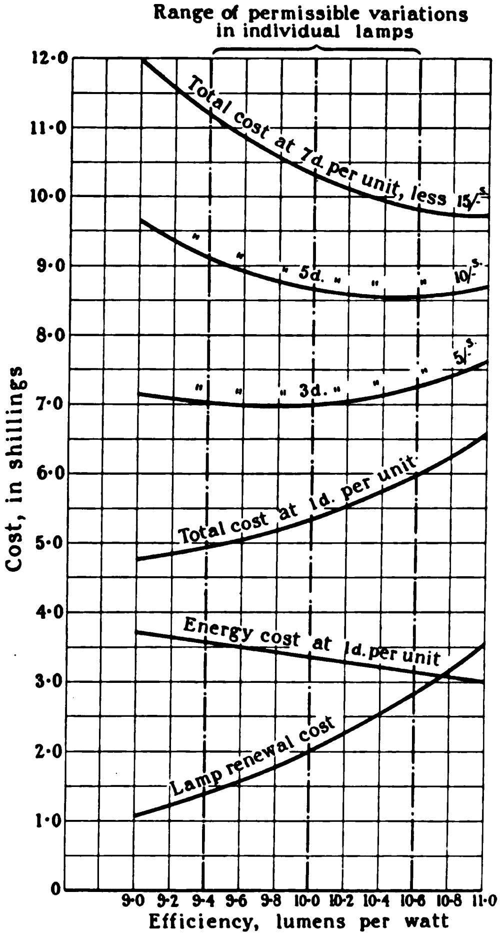
Size of illumination unit required—approx. 30 c.p.
Price of 100-volt lamp of this size—2s.
Normal rating—consumption 40 watts, efficiency 10 lumens per watt,* life 1 000 burning hours.

Table.

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
Efficiency (η) (Normal = 10)	Applied voltage necessary to obtain this with given lamp (Normal = 100)	Life (L) $\propto \left(\frac{1}{\eta}\right)^6$ (Normal = 1 000)	Per 400 000 lumen-hours' illumination		
			Cost of lamp renewals $\frac{1\,000}{L} \times 2s.$	Cost of energy at 3d. per unit $\frac{100}{\eta}$	Total cost
lumens/watt	volts	hours	shillings	shillings	shillings
9	95	1 885	1·06	11·11	12·17
9·2	96	1 650	1·21	10·87	12·08
9·4	97	1 450	1·38	10·64	12·02
9·6	98	1 277	1·57	10·42	11·99
9·8	99	1 129	1·77	10·20	11·97
10	100	1 000	2·00	10·0	12·0
10·2	101	888	2·254	9·804	12·06
10·4	102	791	2·53	9·61	12·14
10·6	103	705	2·838	9·434	12·27
10·8	104	630	3·17	9·26	12·43
11·0	105	563	3·55	9·09	12·64

* This figure is somewhat above present-day efficiencies for this size of lamp, but it will be convenient to have a round number for illustration purposes.

It is proposed to consider the effect of running the above lamps at various efficiencies ranging from 10 per cent below to 10 per cent above the normal (col. 1 of the above table), and this variation can be carried out in a number of ways. Thus a change in applied pressure of about half as much (say from 95 to 105 volts) will produce the required effect (col. 2), and the same result would be achieved by a change in filament diameter from 90 per cent to 110 per cent of the normal, or in filament length from 105 per cent to 95 per cent.*



Any one of these changes would affect also the candle-power of the lamp, but by changing the diameter and length simultaneously the desired efficiency can be obtained without altering the size of the illumination unit. It may be assumed that, whatever the means taken to vary the efficiency, the effect on the life will be the same; and most of the published figures give the life of a tungsten lamp as being inversely proportional to the efficiency raised to a power between 6 and 7. The value of this index is discussed later, but in this case it will be taken as having the value 6 † (col. 3).

Taking as a basis the cost per 1 000 hours of one

* These figures are approximate.
† "Dictionary of Physics," vol. 2, p. 383.

30-c.p. unit (i.e. per 400 000 lumen-hours) the cost of lamp renewals in shillings will be 2 000 ÷ (life in hours) (col. 4), assuming that the 2s. paid per lamp includes any costs incurred in putting it in. With regard to the power consumed, when the filament has been adjusted to give the same candle-power the watts will be 40 divided by the proportionate change in efficiency, and with energy at 3d. the cost for 1 000 hours will be $40 \times 10/\eta \times 3/12 = 100/\eta$ shillings (col. 5). Adding the last two columns gives the total cost for this quantity of illumination, and in the graph the total cost is plotted for energy prices from 1d. to 7d. per unit. By drawing a tangent to the lamp renewal curve through its mid-point the slope at this point is found to correspond to an energy price of 3½d., showing that with energy at this price the lamp is most economical at its rated voltage.

(4) Algebraic Solution.

In working out a general algebraic solution of the above problem it is desirable to know as accurately as possible how the various quantities, and particularly the life, vary with the change of rating. Unfortunately, there is considerable divergence in the published data and it would appear that the simple formula—

$$\text{Life} \propto (\text{Voltage})^{\text{CONSTANT}}$$

is not true for wide variations, nor is the constant the same for different starting temperatures.

This point is chiefly important when excessive over-running is proposed, as when the average life at normal pressure is estimated from a series of "forced" life-tests taken at considerably higher pressures. For economic purposes the degree of over- or under-running is much less than this, and any departure from the simple logarithmic form can probably be safely neglected in comparison with the very wide variations of the other items (cost of energy, etc.) in the problem.

The following symbols will be employed :—

$$\left.\begin{array}{l} V = \text{impressed voltage} \\ F = \text{luminous flux (in lumens)} \\ W = \text{watts consumed} \\ \eta = \text{efficiency (in lumens per watt)} \\ L = \text{life (in 1 000 hours)} \end{array}\right\} \begin{array}{l}\text{with suffix } n \\ \text{to denote the} \\ \text{normal values}\end{array}$$

$$\left.\begin{array}{l} C = \text{first cost of lamp} \\ P = \text{price of energy per kWh} \end{array}\right\} \text{in the same units}$$

It is assumed that all quantities vary according to some simple power of the impressed voltage, and if the latter is varied in the ratio R then

$$\frac{F}{F_n} = \left(\frac{V}{V_n}\right)^a = R^a;\ \frac{W}{W_n} = R^b;\ \frac{\eta}{\eta_n} = R^c \text{ and } \frac{L_n}{L} = R^d\,*$$

where a, b, c and d are fixed constants, provided R is restricted to a fairly small range (say from 0·9 to 1·1). Moreover, as $\eta = F/W$, it follows that c must equal $(a - b)$. In what follows the values will be taken as $a = 3{\cdot}6$, $b = 1{\cdot}5$, $c = 2{\cdot}1$ and $d = 14$ for vacuum tungsten lamps.

* This item is reversed because the life is inversely dependent upon the pressure, and it will be convenient to have all the indices positive.

At the normal rating, for an illumination of F_n lumens lasting 1 000 hours the number of lamps required $= 1/L_n$ and the lamp cost $= C/L_n$. The watts consumed $= W_n$ or F_n/η_n and the energy cost $= PF_n/\eta_n$. Hence the total cost for 1 000 F_n lumen-hours, $T = (C/L_n) + (PF_n/\eta_n)$. Or the total cost for 1 000 lumen-hours, $T' = (C/L_nF_n) + (P/\eta_n)$.

Case 1. *When the same lamps are used, the pressure being varied.*—When the pressure is varied in the ratio R, each lamp will give a flux $F = F_nR^a$ and will have an efficiency $\eta = \eta_nR^c$ and a life $L = L_nR^{-d}$. The total cost per 1 000 lumen-hours then becomes

$$T' = \frac{C}{LF} + \frac{P}{\eta} = \frac{C}{L_nR^{-d}F_nR^a} + \frac{P}{\eta_nR^c} = \frac{C}{L_nF_n}R^{d-a} + \frac{P}{\eta_n}R^{-c}$$

In order to find what ratio of voltage variation will give the minimum total cost, it is only necessary to differentiate T' with respect to R, giving

$$\frac{dT'}{dR} = (d - a)\left[\frac{C}{L_nF_n}R^{(d-a-1)}\right] - c\left[\frac{P}{\eta_n}R^{-(c+1)}\right]$$

This is zero when

$$R^{(d-a+c)} \text{ or } R^{(d-b)} = \frac{c}{d-a}\cdot\frac{P}{C}\cdot\frac{L_nF_n}{\eta_n} = \frac{c}{d-a}\cdot\frac{PL_nW_n}{C}$$

Putting in the above values for the constants, this becomes

$$R^{12\cdot5} = 0{\cdot}202\frac{PW_n}{C}$$

for lamps having a normal life of 1 000 hours.

It will be noted that the above case does not give a true economic comparison, because it results in the illumination being obtained in units of a new size. Thus if 30-watt lamps were proposed and the above calculation showed that the total illumination required would be most economically obtained by over-running the lamps, this might result in the flux per lamp equalling the normal output of a 40-watt lamp. But had it been known that the illumination could permissibly be carried out in the bigger units a saving could have been effected even without over-running, both because of the reduced number of lamps required of the 40-watt size and because of the intrinsically better efficiency of the larger unit.

Case 2. *With a fixed size of illumination unit (giving F_n lumens).*—In this case it will be best to work on the basis of 1 000 F_n lumen-hours, the total cost for which is given above as $T = (CL_n) + (PF_n/\eta_n)$ at the normal rating. When the rating is varied (to an extent equivalent to a pressure change of R) the filament dimensions are so altered that each lamp continues to give F_n lumens, and only the efficiency changes. The number of lamps required at any instant will be the same as before, so that the lamps required per 1 000 hours will still be the reciprocal of the life, and the total cost per 1 000 F_n lumen-hours

$$T = \frac{C}{L} + \frac{PF_n}{\eta} = \frac{CR^d}{L_n} + \frac{PF_n}{\eta_nR^c}$$

Differentiating, we get

$$\frac{dT}{dR} = d\left[\frac{C}{L_n}R^{d-1}\right] - c\left[\frac{PF_n}{\eta_n}R^{-(c+1)}\right]$$

This is zero when

$$R^{c+d} = \frac{c}{d}\cdot\frac{P}{C}\cdot\frac{F_nL_n}{\eta_n} \quad\text{or}\quad \frac{c}{d}\cdot\frac{P}{C}W_nL_n$$

Putting in the above values for the constants, this becomes

$$R^{16\cdot 1} = 0\cdot 15\frac{P}{C}W_nL_n = 0\cdot 15\frac{PW_n}{C}$$

for lamps having a normal life of 1 000 hours.

This formula can be explained as follows with reference to the curves already plotted. Maximum economy occurs when the slopes of the curves of energy cost and lamp cost are equal and opposite. If these are plotted to a base of rating measured in efficiency, the former will be a straight line and the latter a curve the shape of which depends on the efficiency/life index (c/d). The slopes will therefore depend upon the values of these indices and also on the multiplying constants—so that *at any one rating* maximum economy will occur when a particular ratio exists between the money normally spent on lamps ($\propto C/L_n$) and that spent on energy ($\propto PW_n$). This explains the appearance in the formula of items representing not only the energy and lamp prices but also the size of lamp.

(5) Application.

Taking the simplest form of the above, with constants for a vacuum tungsten lamp, namely $R^{16\cdot 1} = 0\cdot 15PW_n/C$, this can be applied to the case already considered of lamps costing 2s. each and having a normal rating of 40 watts. For a fixed size of illumination unit (which will be about 30 mean spherical candle-power for a 100-volt lamp) the most economical point at which to run will be given :—

With energy at 1d., by $R^{16\cdot 1} = \dfrac{0\cdot 15 \times 1 \times 40}{2 \times 12}$, whence $R = 0\cdot 917$, i.e. 91·7 per cent of normal pressure, or approx. 83·4 per cent normal efficiency.

With energy at 4d., by $R^{16\cdot 1} = 4/4$, whence $R =$ unity, i.e. 100 per cent of normal pressure, and efficiency.

With energy at 7d., by $R^{16\cdot 1} = 7/4$, whence $R = 1\cdot 035$, i.e. 103·5 per cent of normal pressure, or approx. 107 per cent normal efficiency.

These agree fairly closely with the graphical points, allowing for the fact that in the graphs the index c is taken as 2 and the ratio d/c as 6.*

Reference should here be made to the figures published by H. Bohle in his book "Electrical Photometry and Illumination" (1912, new edition recently published). Working on a curve connecting watts per candle-power and relative life, he considers a single size of tungsten lamp having a normal rating of 60 watts and costing 2s. 6d. He finds that when energy costs 4d. a unit this lamp is most economical on its normal rating, giving 1 000 hours' life and taking 1·2 watts per mean horizontal candle-power. When energy costs 6d. it is economical to over-run the lamp until it takes only 1·03 watts per mean spherical candle-power, whereas with energy at 2d. the specific consumption should be 1·35. As the size of the illumination unit is allowed to vary, these results must be compared with the first of the two formulæ developed above, and, allowing for slight differences in the indices employed, there is very general agreement.

In considering the conclusions to be drawn from the above formula, it should be noted in the first place that of the three variables, the lamp prices vary least, e.g. from about 2s. to 2s. 6d. for vacuum lamps, the lamp sizes vary more—say from 10 or 20 to 60 watts for these lamps—whilst the energy prices vary most, since they may range from 1d. to 8d. a unit or even more.

With regard to lamp size and price, it is clear that the larger or the less expensive the lamp, the more it should be over-run and the shorter should be the life aimed at. Thus, taking as a starting-point the 40-watt lamp costing 2s., which is economical on its present-day rating with energy at 4d. a unit, it is evident that with this energy price any lamp in which the lamp size in watts divided by the price in shillings exceeds 20 should be over-run. With a 60-watt lamp costing 2s. 3d., $R^{16\cdot 1}$ should equal $1\frac{1}{3}$, whence $R = 1\cdot 018$ and, as the life $L = L_nR^{-14}$, the best life will be $1\,000/1\cdot 018^{14}$ = 882 hours. On the other hand, with a 20-watt lamp costing, say, 2s. 6d., the most economical life (with energy at 4d.) will be 2 230 hours. If the lamp price were proportional to the size in watts these items would, of course, cancel out, but unfortunately the price varies little (and sometimes inversely) with the size, and it would certainly appear that manufacturers should make some attempt to rate their lamps accordingly, even though they take no account of variations in the price of energy.

Coming now to the third variable, viz. cost of energy, this is chiefly a problem for the consumer; but even here the manufacturers could help by grading their lamps for dear, medium and cheap energy, somewhat on the lines of the "three-voltage rating" suggested some years ago in competing with the carbon lamp for cheap energies.*

It will be noted that the B.E.S.A. Specification permits deviations in efficiency of about 6 per cent on either side of the specified normal—represented by the upright lines on the graph—and, when these variations occur, the consumer (on specially cheap or dear circuits) could be given the opportunity of choosing them in place of the normal lamps.

If no such help is forthcoming for the lamp user he must needs act for himself, and the difficulty of so doing is that whilst a considerable range of voltage

* With these values for the indices, the normal rating coincides with the most economical one for an energy price of 3½d., and for other energy prices the formula gives the most economical rating as follows :—

Energy at 1d.—Rating should be 91·2 per cent of normal pressure or 82·5 per cent of normal efficiency.
Energy at 3d.—Rating should be 98·7 per cent of normal pressure or 97·4 per cent of normal efficiency.
Energy at 5d.—Rating should be 102·6 per cent of normal pressure or 105·2 per cent of normal efficiency.
Energy at 7d.—Rating should be 104·7 per cent of normal pressure or 109·4 per cent of normal efficiency.

* See, especially, R. W. Hutchinson: "High-Efficiency Electric Illuminants."

atings is available, the number of sizes is very limited, and, unfortunately, re-rating by voltage alone alters the size of the illumination unit. Thus if the circuit voltage is 110 and lamps of about the 40-watt size are desired, the normal flux from such a lamp is 370 lumens. Assuming that 2s. is the price of the lamp, whatever the size or rating, the above calculation shows that with energy at 1d. a unit the most economical rating is that corresponding to 91·7 per cent of the normal voltage, or about 73 per cent of the normal candle-power. This can be exactly effected by fitting 120-volt lamps, but if, say, the 60-watt size is chosen, the lamp flux will be 415 lumens instead of 370.

Taking as the other extreme a circuit with energy at 8d. a unit, the calculation shows an economic rating of 104·4 per cent of the normal voltage. This requires lamps designed for a pressure of about 105 volts, and a 30-watt lamp of this type will then give 320 lumens when run on 110 volts. Such small changes in the size of the illumination unit are not necessarily disadvantageous, since there is no special virtue in the particular candle-powers associated with 30, 40 and 60 watts, and in any given case some intermediate values may be as good or better. It should be realized, however, that any such change will modify the economic calculation, since this is based on the assumption that lamps are available giving the original candle-power at the new rating.

Other Considerations.

So far, only initial conditions have been considered. As a lamp is used, its filament deteriorates to some extent, causing in the first place a loss in candle-power and secondly a loss in efficiency (since the filament is virtually smaller and therefore under-run). This deterioration is far less than it was with the older type of lamps, in which the life was frequently defined not as its life up to breaking point, but that up to when it gave 80 per cent of its initial candle-power. With the modern tungsten lamp it is rare for even an individual lamp to last until it becomes uneconomical on account of diminished efficiency, and the mean efficiency of a modern lamp should be over 90 per cent of the initial efficiency.

It is difficult to determine exactly what effect deterioration should have upon the economic calculation, without further data as to how the deterioration affects the values of the indices. It is safe to say, however, that in comparison with the wide range of the other variables entering into the problem, its effect on the economic position will be slight, and its chief result is a lowering of the mean size of the illumination unit.

When several energy prices rule—as when the first portion of the consumption is charged for at a higher rate—the economic choice should not be affected, since a change in efficiency will not affect the time distribution of the consumption. In such a case it is only necessary to employ in the formula the mean price paid per unit of lighting energy over the period in question.

Qualitative effects have been ignored throughout, but it is obvious that on a very cheap energy circuit it might pay to under-run lamps to such a point that the light became too red for satisfactory illumination. Other limits to under-running when energy is very cheap would be vibration (causing the lamp to break before its calculated life period) and interest on capital. The latter could not safely be neglected if excessive under-running (and long life) were proposed or if the service were highly intermittent. Its cost could be brought into the problem if the annual hours of service were fixed and known.

(7) Conclusions.

The purpose of the present paper has been not so much to arrive at any novel results as to emphasize facts not generally realized and to suggest possible courses of action by the manufacturer or the lamp user. The vital connection between rating and economy, and their sensitive dependence upon pressure, are at last being recognized, and Mr. C. W. Sully, speaking at the World Power Conference on behalf of the Electric Lamp Manufacturers Association of Great Britain, said: "It is therefore extremely important that lamps should be operated at their rated voltage. . . . It is equally necessary that supply voltages should be as definite and constant as possible, in order that lamp manufacturers may rate their lamps at the most economical efficiency." But the problem is regarded too statically, and of the many recent attempts at educating the public in the proper use of lamps there has hardly been one pointing out that the correct rating is not something fixed by nature or the lamp manufacturers but should depend on circumstances and, in particular, upon the energy price and the lamp size. To cite a particular case, until recently the author was paying 7d. a unit for all his lighting energy, whilst blocks of flats near by were buying their energy at a uniform price of 1d. Lamps which were economical for the one circuit would be quite unsuitable for the other, yet the same shop served them both, and there was nothing on the lamps or their wrappers to show that they were not suitable for the same voltage under all possible circumstances. In a similar way 20-watt and 60-watt lamps for the same circuit should be designed to have quite different lengths of life.

The energy price is admittedly the most difficult item in the problem, and the above suggestions make no pretence of exhausting the possibilities. But, however difficult, there can be no denying the importance of the problem, in view of the fact that the energy cost may frequently represent 90 per cent or more of the total cost of the illumination, and that the energy price may vary as much as from 1d. to 8d. a unit. In the absence of any more positive action or assistance for the consumer, it would appear that the least that could be done would be to stamp on the lamp or wrapper the particular energy price as well as the voltage for which the rating was determined.

INTERFERENCE BETWEEN CIRCUITS IN CONTINUOUSLY LOADED TELEPHONE CABLES.*†

By A. ROSEN, B.Sc. (Eng.), Ph.D., Associate Member.

(*Paper received 12th January, 1926.*)

SUMMARY.

This paper is concerned with the interference between circuits in homogeneous cables, and its reduction. The line is replaced by its equivalent network, and, in the case of a four-wire group as used in superimposed circuits, the network consists of six members. The relations between the induced and inducing currents and voltages are established, and a quantitative definition of interference is given. The effects of unbalances in the line constants are discussed, and the influence of distance and frequency is investigated. An account is given of methods of measurement and of the means of reducing interference in cables, and a method developed by the author for dealing with the difficulties introduced by the distributed inductance in continuous loading is described.

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LIST OF SYMBOLS OF FREQUENT OCCURRENCE.

A, B, C, D = the four wires of a quad.
Z_s = impedance of side circuit.
Z_1 = impedance of side circuit AB.
Z_2 = impedance of side circuit CD.
Z_p = impedance of phantom circuit AB/CD (+).
Y_1 = admittance of side circuit AB.
Y_2 = admittance of side circuit CD.
Y_p = admittance of phantom circuit AB/CD.
Z_{01} = characteristic impedance of circuit AB.
Y_{01} = characteristic admittance of circuit AB.
W, X, Y, Z, M, N = admittances between the points A, B, C, D.

* Thesis approved for the degree of Doctor of Philosophy in the University of London.

† The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

$\overline{W}$ = mean of W, X, Y, Z.
$\overline{M}$ = mean of M, N.
P, Q, R, S = admittance differences.
$\frac{1}{2}F, -\frac{1}{2}G, -\frac{1}{2}H$ = interference coefficients.
J = general interference coefficient.
g = leakance component of interference coefficient.
c = capacity component of interference coefficient.
f = frequency in cycles per second.
ω = frequency in radians per second.
$j = \sqrt{(-1)}$.
l = length of circuit.
R = resistance per unit length.
L = inductance per unit length.
G = leakance per unit length.
C = capacity per unit length.
Z = line impedance = $R + j\omega L$.
Y = line admittance = $G + j\omega C$.
Z_0 = characteristic impedance.
γ = propagation constant.
β = attenuation constant.
α = wave-length constant.
V_1 = voltage on disturbing circuit.
V_2 = voltage on disturbed circuit.
I_1 = current in disturbing circuit.
I_2 = current in disturbed circuit.
I_t = current in telephone receiver.
Z_t = impedance of telephone receiver.
Ψ = interference expressed in power ratio basis.
ψ = interference expressed in equivalent current ratio basis.

Section 1. INTRODUCTION.

Interference between circuits is of importance as being one of the factors which limit the distance over which satisfactory telephonic communication can be effected; since the introduction of thermionic valve repeaters its position in this respect has been emphasized.

If we consider a transmission system on two circuits of which two simultaneous conversations are taking place, we can imagine that at some particular instant there is a voltage V impressed on the near end of circuit 1, and at the same time an equal voltage V impressed on the distant end of circuit 2. At the near end of circuit 2, there will be a voltage kV due to the speech on that line, where k is a factor which depends on the attenuation of the line, and also a voltage $k'V$ due to the interference from circuit 1. Obviously k' must be much smaller than k, otherwise the interference would make the received speech on circuit 2 unintelligible; so that to a certain extent the lowest value of k is governed by the lowest value to which k' can be reduced. The use of amplifiers has made it possible to reduce k very considerably, the line losses being made good by the repeaters, but in order to take full advantage of this amplification the interference between circuits must be reduced in like proportion. This is perhaps most important in the case of a long submarine cable where, on account of the limitations of weight, the size is restricted; it is desired to obtain the largest number of circuits, and this entails working with the maximum value of attenuation that the repeaters will allow. This can only be done if the interference is kept small.

Again, it is undesirable that any appreciable volume of speech should be overheard from another circuit, as this would do away with the secrecy of the individual line, which is regarded as one of the advantages of line telephony as compared, for example, with radio telephony in its present stage of advancement.

The form of the attenuation factor and its dependence on the constants of the line are well known. In this paper the interference factor is discussed and its relation to the other properties of the line investigated.

The subject has received considerable attention during recent years, notably in Germany, where important contributions have been published.*

In this paper the problem has been attacked from a new view-point, and the results obtained are expressed in a form in which they can be applied to practical working. Methods of measurement are described, and the means of reducing interference discussed, in particular a system which the author has developed to deal with cases in which the methods at present in use break down.

Section 2. GENERAL CONSIDERATIONS.

(i) *Phantom circuit.*—The arrangements for obtaining the superimposed or phantom circuit are shown diagrammatically in Fig. 1.

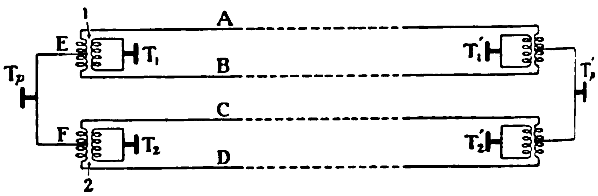


FIG. 1.—Phantom circuit.

The loops AB, CD, commonly known as the "side circuits," are terminated by transformers at both ends. Telephones T_1, T_2, are connected to the primary windings; the secondary windings are divided into carefully balanced halves, the mid-points being joined by the telephones T_p.

The following is an elementary explanation of the action of the phantom circuit; the fuller mathematical treatment is given later. When speaking into T_p, the current into transformer secondary 1 divides, having the choice of two paths, along A returning via CD, and along B returning via CD. If these paths offer equal impedance, the currents will be equal, consequently there will be no resultant magnetic field in the core of the transformer, and no current in the telephone T_1. Similarly there will be no current in T_2 if the impedances of the paths C/AB and D/AB are equal. When speaking on T_1, the transformer 1 will function in the normal way and points A and B will be at opposite

* LICHTENSTEIN: *Elektrotechnische Zeitschrift*, 1920, vol. 41, p. 188; BREISIG: *ibid.*, 1921, vol. 42, p. 933: DOHMEN and KÜPFMÜLLER: *ibid.*, 1924, vol. 45, p. 266, and KÜPFMÜLLER: *Archiv für Elektrotechnik*, 1923, vol. 12, p. 160.

potentials with regard to circuit CD. Here again, if the impedances A/CD and B/CD are equal, these potentials will be equal and opposite; consequently there will be no P.D. between the mid-point E and CD, and no current in the telephone T_p.

The super-phantom circuit is obtained by an extension of this principle. A, B, C, D (Fig. 2) represent one group of four wires, and H, I, J, K a second group of four wires. The mid-points of the transformers 1, 2, 3, 4, are connected to two further transformers, 5, 6, the mid-points of which are joined through the telephones T_{pp}. T_1, T_2, T_3, T_4 serve the side circuits,

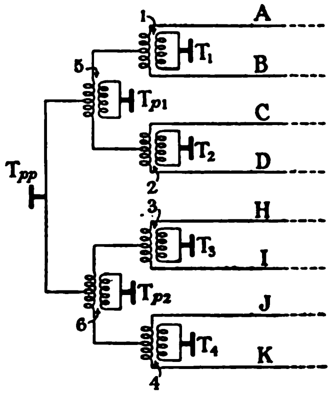
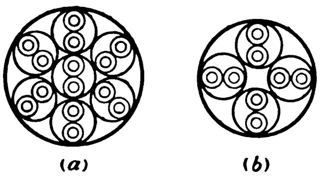


FIG. 2.—Super-phantom circuit.

T_{p1} and T_{p2} the phantom circuits, and T_{pp} the super-phantom circuit. In the phantom circuit A and B function in parallel as a single wire, and similarly the pairs CD, HI, JK. In the super-phantom circuit A, B, C, D function in parallel as a single wire, as do H, I, J, K.

(ii) *Forms of cable construction.*—It will be seen that the use of the phantom circuit entails the grouping of the wires in fours, in such a way that the characteristics of each individual within that group are the same.



(*a*) (*b*)

FIG. 3.—Twin cables.

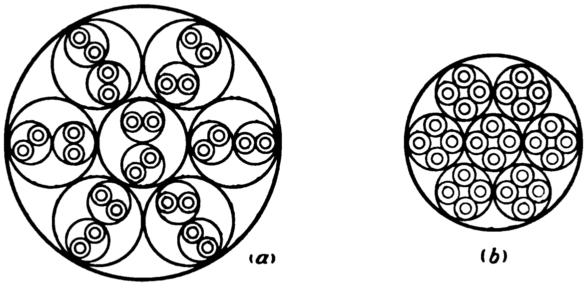
This has led to the development of the four-wire grouping in cables intended for superimposed working.

The principal forms of construction of telephone cables are (1) with the pair as unit, (2) with a group of four wires or quad as unit.

(1) In this class the cable is built up of pairs stranded together in one or more layers; it is not suitable for superimposing except in the special case of four pairs, where the diagonally opposite pairs constitute the phantom circuits (Figs. 3*a* and 3*b*).

(2) The quads may be built up in two ways, (*a*) star form, in which the four wires are laid up together, (*b*) multiple twin form in which two pairs are laid up together. The quads are then stranded into layers in the usual way. The multiple twin (Fig. 4*a*) has inherently a better balance in its capacity characteristics and is the type generally adopted for trunk lines. The star form, however, occupies a smaller space, and is used for submarine cables, where this is an important consideration (Fig. 4*b*).

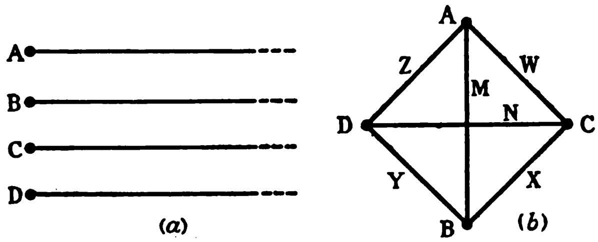
(iii) *The equivalent network.*—There are two methods of approaching the problems of interference between circuits; in the first (which is the usual one adopted) the line is considered along its length; in the second the circuits are regarded from one end and, so to speak, a cross-sectional view is taken. The author has found the latter aspect of great assistance and it has been adopted generally in the discussions which follow.



(*a*) (*b*)

FIG. 4.—Q lead cables, (*a*) 7-quad multiple twin, (*b*) 7-quad star.

G. A. Campbell gives the following theorem in his paper on "Cisoidal Oscillations": * "If we retain a group of terminals as the only accessible part, any network may be replaced either by a set of direct impedances connecting the terminals in pairs, or by a set of mutual impedances between branches radiating from a common point and terminating one at each of the terminals. In the first case all mutual impedances



(*a*) (*b*)

FIG. 5.—Line and equivalent network.

are avoided; in the second case all self-impedances are avoided." Consequently, if we have a transmission line containing a number of wires which terminate at the end nearer us at points A, B, C . . . etc. we may, as regards the effect on external apparatus at this end, replace the line by a system of conductors joining every pair of the points A, B, C . . . etc. In particular the quad ABCD in Fig. 5 (*a*) may be replaced by the six-member network AC, CB, BD, DA, AB, CD, in Fig. 5 (*b*). The values of the members will depend on the nature of the line and how it is terminated.

For all the theoretical work the values, unless other-

* *Transactions of the American I.E.E.*, 1911, vol. 30, p. 890.

wise indicated, are admittance operators, these being generally the better to work with. In practical work, however, impedance operators are usually considered, and the formulæ, where necessary, are given also in that form. When there is a possibility of doubt, y or z respectively will be used as a distinguishing suffix.

(iv) *Quad composed of two symmetrical pairs* AB, CD.—Each pair is symmetrical with regard to all the other wires in the cable and earth. Hence AB is symmetrical about the axis CD, i.e. $W = X$ and $Z = Y$; also CD is symmetrical about the axis AB, i.e. $W = Z$ and $X = Y$. Thus $W = X = Y = Z = \overline{W}$.

Admittance of the side-circuit AB,

$$Y_1 = \overline{W} + M \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Admittance of the side-circuit CD,

$$Y_2 = \overline{W} + N \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Admittance of the phantom circuit,

$$Y_p = 4\overline{W} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

In any practical case these three admittances, Y_1, Y_2 and Y_p, are easily measured or calculated, and thus the values of our equivalent network members are known.

From these values it is possible to calculate the effective admittance of the quad under various conditions. For example :—

(1) Between AC and BD. By inspection, the admittance is

$$2\overline{W} + M + N = Y_1 + Y_2 \quad . \quad . \quad . \quad (4)$$

(2) Between ABC and D. By inspection, the admittance is

$$2\overline{W} + N = \tfrac{1}{4}Y_p + Y_2 \quad . \quad . \quad . \quad (5)$$

(3) Between A and C, B and D being free.

First transform the star AB, CB, DB into the mesh ADC,* the new values being shown in Fig. 6. From this triangle the admittance between AC is easily calculated, the value being

$$Y_{ac} = \frac{4\overline{W}(\overline{W} + M)(\overline{W} + N)}{(2\overline{W} + M)(2\overline{W} + N) - \overline{W}^2}$$

$$= \frac{Y_p Y_1 Y_2}{Y_1 Y_2 + \frac{1}{4}Y_p(Y_1 + Y_2)} \quad . \quad . \quad . \quad (6y)$$

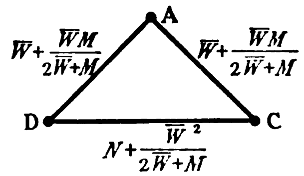


FIG. 6.—Point B eliminated.

Expressing this in impedances, we get the following simple result :—

$$Z_{ac} = Z_p + \tfrac{1}{4}(Z_1 + Z_2) \quad . \quad . \quad . \quad (6z)$$

(v) *Practical confirmation.*—These results provide a ready means of testing the validity of the application of Campbell's network theorem to the telephone transmission line.

* See Appendix I.

TABLE 1.

	Readings		Calculated from readings		Calculated from formulæ	
	r	C	Admittance $\frac{1}{r} \pm j\omega C$	Impedance $\frac{r \mp j\omega C r^2}{1 + \omega^2 C^2 r^2}$	Admittance	Impedance
Distant End Open.						
	ohms	μF	mhos × 10³	ohms	mhos × 10³	ohms
Side AB	8 070	0·458	0·1238 + 2·29 j	23·6 − 436 j	—	—
Side CD	8 050	0·458	0·1242 + 2·29 j	23·6 − 436 j	—	—
Phantom AB/CD ..	1 658	1·434	0·602 + 7·17 j	11·68 − 138·9 j	—	—
AC/BD	3 990	0·916	0·250 + 4·58 j	—	0·248 + 4·58 j	—
ABC/D	3 645	0·818	0·275 + 4·09 j	—	0·275 + 4·08 j	—
A/C (BD free) ..	5 470	0·560	—	23·3 − 356 j	—	23·5 − 357 j
Distant End Closed.						
Side AB	2 150	0·440	0·465 − 2·20 j	92·0 + 435 j	—	—
Side CD	2 127	0·441	0·471 − 2·22 j	91·3 + 431 j	—	—
Phantom AB/CD ..	972	0·830	1·029 − 4·15 j	56·4 + 227 j	—	—
AC/BD	1 065	0·885	0·939 − 4·42 j	—	0·936 − 4·42 j	—
ABC/D	1 377	0·651	0·726 − 3·25 j	—	0·728 − 3·26 j	—
A/C (BD free) ..	2 031	0·428	—	102·1 + 444·2 j	—	102·2 + 444 j

ω = 5 000 radians per second.

Tests were carried out on a length of continuously loaded cable using an angular frequency of $\omega = 5\,000$. The impedance of a quad was measured with various arrangements of connections of the cores. Two sets of readings were taken, first with the distant end open, and secondly with the distant end short-circuited. The bridge used is illustrated in Fig. 7. R_1, R_2 are equal non-inductive resistances of 1 000 ohms each, r a variable non-inductive resistance, C a variable condenser; C is connected across arm CD or BC according

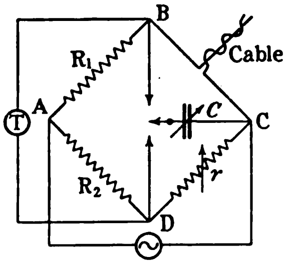


FIG. 7.—Bridge for measuring impedance.

as the angle of the admittance measured is positive or negative. The admittance of the cable is $1/r \pm j\omega C$, where r is in ohms and C in farads, $\omega = 2\pi \times$ frequency; expressed as an impedance the result is

$$\frac{r(1 \mp j\omega Cr)}{1 + \omega^2 C^2 r^2}$$

It will be seen that formulæ (4), (5) and (6z) above are simple additions of vectors. For the first two the result is required in admittance form, and for the last as an impedance.

The results given in Table 1 show a close agreement between the calculated and the measured values, and prove that a telephone line consisting of a number of

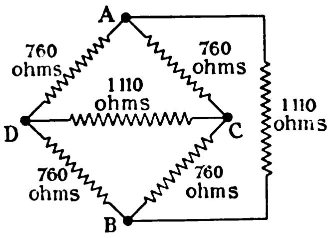


FIG. 8.—Resistance network.

conductors can be treated as a network of impedances joining the terminals at one end. The slight discrepancies shown in the table may be attributed to the small unbalances between the cores, and also to the following facts:—The inductance of a continuously loaded cable varies somewhat with the current, as the permeability of the iron alters with the strength of field; and the distribution of current in the conductors would have to be the same for all the different ways of connections if the relations are to be rigidly fulfilled.

(vi) *The infinite line and terminating networks.*—When the line is infinitely long, Y_1, Y_2, Y_p become Y_{01}, Y_{02}, Y_{0p}, the characteristic admittance of the two side and phantom circuits respectively. The corresponding six-member network will represent the infinite line in every respect. Hence if a finite line having these characteristic admittances be terminated by such a network, it will behave in every way as if it were itself infinitely long. In the following discussion, when a line is terminated by a network equivalent to the infinite line it will be spoken of as "terminated."

Generally, the characteristic impedance of a loaded line is a vector having a small angle, and in practice it is approximated to by a plain resistance. The terminating network for a loaded line can thus consist of

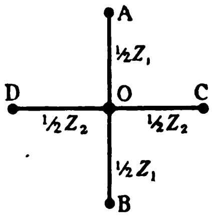


FIG. 9.—Star network.

six suitably chosen resistances. For one cable the following figures were obtained:—

Characteristic impedance of side circuits = 480 ohms.
Characteristic impedance of phantom circuit = 190 ohms.

In the corresponding terminating network (Fig. 8)

$$\begin{aligned} AD = BD = AC &= BC \\ &= 4 \times 190 = 760 \text{ ohms} \\ AB = CD &= \frac{760 \times 480}{760 + 480} = 1\,110 \text{ ohms} \end{aligned}$$

Further, with a loaded line, the value of the characteristic impedance does not alter greatly with frequency, so that a network chosen on the values at a mean frequency (e.g. $\omega = 5\,000$) will represent the infinite line for actual speech.

In the case where the phantom impedance is half

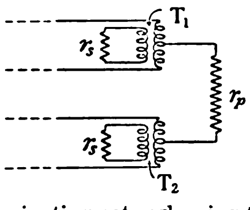


FIG. 10.—Terminating network using transformers.

the mean of the impedances of the side circuits, the six-member network may be reduced to the simple star form (Fig. 9) with $OA = OB = \frac{1}{2}Z_1$ and $OC = OD = \frac{1}{2}Z_2$.

(vii) *Other types of terminating network.*—That used by the British Post Office is shown in Fig. 10. T_1, T_2 are transformers similar to those at the sending end. The primaries are closed through resistances r_s, the mid-points of the secondaries being joined by a resistance r_p. If r is the resistance of one half of each transformer winding, the resistances are chosen so that

$$\left.\begin{aligned} r_s + 4r &= Z_s \\ r_p + r &= Z_p \end{aligned}\right\} \quad \ldots \ldots \quad (7)$$

The arrangement shown in Fig. 11 is used in American practice, choke coils C_1, C_2, being employed instead of transformers. The values of the resistances are :—

$$\left.\begin{aligned} r_s &= Z_s \\ r_p + r &= Z_p \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Section 3. THE INTERFERENCE PROBLEM.

(i) *Definitions.*—In English, a certain confusion exists regarding the use of terms, e.g. the word "cross-talk" is applied to all classes of interference and also to one particular kind. The author uses "interference" in this paper to designate the general phenomenon, this corresponding to the German word "nebensprechen." Interference between circuits may be divided into two classes, (*a*) "cross-talk" between circuits which are physically separate, (*b*) "overhearing" between circuits which have a common metallic path.

Cross-talk includes interference between :—

(i) Side circuit and side circuit in the same quad,
(ii) Side circuit and side circuit in another quad,
(iii) Side circuit and phantom circuit on another quad,
(iv) Phantom circuit and phantom circuit on another quad.

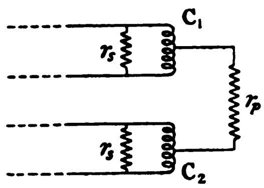


FIG. 11.—Terminating network using choke coils.

Overhearing includes interference between :—

(i) Side circuit and phantom circuit on the same quad,
(ii) Side circuit and super-phantom circuit on the same quad,
(iii) Phantom circuit and super-phantom circuit on the same quad.

Cross-talk corresponds to the German word "übersprechen" and overhearing to the German "mitsprechen."

Interference may be defined quantitatively as the ratio of the power in the disturbed to that in the disturbing circuit. Obviously this ratio will depend on the circuit conditions, and in the case of uniform transmission lines it is desirable to define these explicitly. Before this is done, however, the relations between the currents and voltages in the general case will be obtained.

We have so far considered the components of each pair of wires to be perfectly symmetrical. In practice unbalances occur, and these give rise to interference between the circuits.

Fig. 12 represents the equivalent network of a quad ABCD, the values being admittances.

Let
$$\begin{aligned} W - X &= P \\ Z - Y &= Q \\ W - Z &= R \\ X - Y &= S \\ W + X + Y + Z &= 4\overline{W} \end{aligned}$$

It is assumed that the unbalances are not so great as seriously to upset the symmetry of the pairs, i.e. P, Q, R, S are small compared with $\overline{W}$.

Further, let
$$\begin{aligned} P - Q = R - S &= F \\ P + Q &= G \\ R + S &= H \end{aligned}$$

F, G, H are proportional to the interference coeffi-

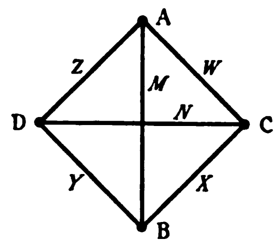


FIG. 12.—Generalized network.

cients, and will always be expressed as admittance vectors.

The network can be regarded as a Wheatstone bridge, and we shall first determine the relation between the voltages in this type of network.

(ii) *Wheatstone network.*—In Fig. 13 (*a*), A, B, C, D represent the four corners of the bridge, the supply of P.D. = V_1 being across AB; to determine the P.D. across the detector arm CD.

Let B be at zero potential, and let the potential of

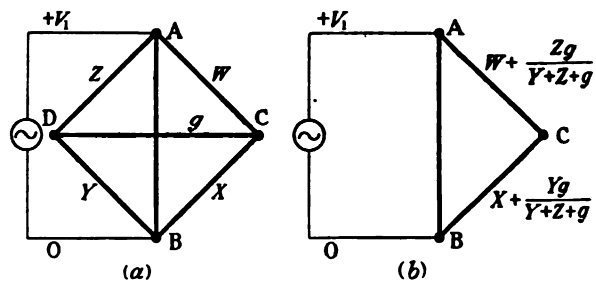


FIG. 13.—Wheatstone network.

A be $+V_1$. Transform star AD, CD, BD (Fig. 13*a*) into mesh AC, BC, AB (Fig. 13*b*).

Then
$$\mathrm{AC} = W + \frac{Zg}{Y + Z + g}$$
$$\mathrm{BC} = X + \frac{Yg}{Y + Z + g}$$

$$\text{Potential of C} = \frac{\mathrm{AC}}{\mathrm{AC} + \mathrm{BC}} V_1$$
$$= \frac{W(Y + Z + g) + Zg}{(W + X)(Y + Z + g) + (Y + Z)g} V_1$$

By symmetry,
$$\text{potential of D} = \frac{Z(W + X + g) + Wg}{(Y + Z)(W + X + g) + (W + X)g} V_1$$

$\therefore$ P.D. across CD, V_2 = potential of C − potential of D

$$= \frac{WY - XZ}{(W + X + Y + Z)g + (W + X)(Y + Z)} V_1 \quad (9)$$

(iii) *Cross-talk.*

(*a*) *Supply* $= V_1$ *volts, and telephone of admittance* Y_t *connected directly to the cable.*

Case (*i*). *Source on* AB, *listening on* CD, (AB/CD).—Let the voltage on CD $= V_2$.

Then from (9)

$$\frac{V_2}{V_1} = \frac{WY - XZ}{4\overline{W}(N + Y_t) + (W + X)(Y + Z)}$$

It is easy to show by direct substitution that

$$WY - XZ = (P - Q)\overline{W} - \tfrac{1}{4}(P + Q)(R + S)$$

Also $$(W + X)(Y + Z) \simeq 4\overline{W}^2$$

$$\therefore \frac{V_2}{V_1} = \frac{F - (GH/4\overline{W})}{4(\overline{W} + N + Y_t)} \quad . \quad . \quad . \quad (10)$$

Generally $GH/4\overline{W}$ is negligibly small compared with F; also $W + N = Y_2$, the admittance of circuit CD.

$$\therefore \frac{V_2}{V_1} = \frac{F}{4(Y_2 + Y_t)} \quad . \quad . \quad . \quad (11y)$$

Expressed in impedances,

$$V_2 = \frac{Z_2 Z_t}{Z_2 + Z_t} \cdot \frac{F}{4} V_1 \quad . \quad . \quad . \quad (11z)$$

Current in telephones,

$$I_t = \frac{Z_2}{Z_2 + Z_t} \cdot \frac{F}{4} V_1 \quad . \quad . \quad . \quad (12z)$$

Case (*ii*). *Source on* CD, *listening on* AB, (CD/AB).—Let the voltage on AB $= V_2$.

Then $$\frac{V_2}{V_1} = \frac{F}{4(Y_1 + Z_t)} \quad . \quad . \quad . \quad . \quad (13y)$$

etc.

(*b*) *The supply and telephone connected to the cable through transformers of* 1 : 1 *ratio, the primary and secondary being divided.*

Let r_z = impedance of each half of primary or secondary. For side-circuit currents, the impedance $= 4r_z$ + impedance in secondary circuit; for superimposed currents, impedance $= \frac{1}{2}r_z$ per transformer.

Case (*i*). *Source on* AB, *listening on* CD (AB/CD).—Due to the transformer on CD, $4r_z$ has to be added to Z_t in equations (11*z*) and (12*z*); further, due to the transformer on AB, the voltage across the cable is less than that applied, in the ratio $Z_1/(Z_1 + 4r_z)$.

Therefore, expressed in impedances,

$$\frac{V_2}{V_1} = \frac{Z_1 Z_2 (Z_t + 4r)}{(Z_1 + 4r)(Z_2 + Z_t + 4r)} \cdot \frac{F}{4} \quad . \quad (14z)$$

and current in telephones

$$I_t = \frac{Z_1 Z_2}{(Z_1 + 4r)(Z_2 + Z_t + 4r)} \cdot \frac{F}{4} V_1 \quad . \quad (15z)$$

Case (*ii*). *Source on* CD, *listening on* AB, (CD/AB).—The equations for V_2 and I_t are the same as (14*z*) and (15*z*), but Z_1 and Z_2 are interchanged.

(iv) *Overhearing.*

(*a*) Let us first consider the more direct case in which equal ratio arms are used to obtain the super-

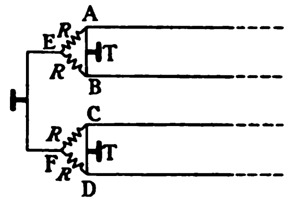


FIG. 14.—Phantom circuit employing resistances.

imposing effect (Fig. 14). Fig. 15 shows the equivalent network at the sending end, all the values being admittances. Whether the source is on AB and the detector on EF (phantom) or vice versa, it is evident from Fig. 15 that since W, X, Y and Z are all approxi-

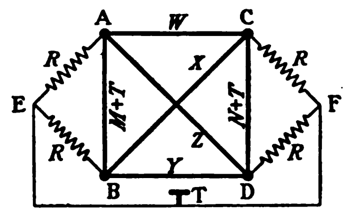


FIG. 15.—Network equivalent to Fig. 14.

mately equal, the points C and D will be at practically the same potential, and therefore the admittance across CD may be neglected. This enables us to simplify the diagram (Fig. 15) in one operation by converting the three-ray stars AC, BC, FC and AD, BD, FD into

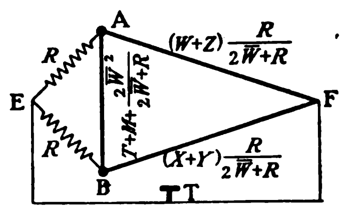


FIG. 16.—Result of eliminating points C and D.

the mesh ABF. The resulting system is shown in Fig. 16.

$$\mathrm{AF} = \frac{(W + Z)R}{2\overline{W} + R}$$

$$\mathrm{BF} = \frac{(X + Y)R}{2\overline{W} + R}$$

$$\mathrm{AB} = M + T + \frac{2\overline{W}^2}{2\overline{W} + R}$$

(The same result can be obtained without neglecting CD, but this involves three stages of transformation.)

Case (*i*). *Supply on phantom* EF, *listening on side* AB, (+/AB).—From equation (9),

$$\frac{V_2}{V_1} = \frac{(X + Y - W - Z)R^2/(2\overline{W} + R)}{[2R + 4\overline{W}R/(2\overline{W} + R)]\,[M + T + 2\overline{W}^2/(2\overline{W} + R)] + [R + 2\overline{W}R/(2\overline{W} + R)]^2}$$

$$= \frac{-(P + Q)}{[1 + (4\overline{W}/R)]\,(2\overline{W} + 2M + R + 2T)}$$

$$= \frac{-G}{2Y_1[1 + Y_p/R]\,[1 + R/(2Y_1) + T/Y_1]} \quad \ldots \quad (16y)$$

Expressed in impedances,

$$\frac{V_2}{V_1} = \frac{-Z_1G}{2[1 + R_z/Z_p]\,[1 + Z_1/(2R_z) + Z_1/T_z]} \quad (16z)$$

Case (*ii*). *Supply on side* AB, *listening on phantom* EF, (AB/+).—From equation (9),

$$\frac{V_2}{V_1} = \frac{(X + Y - W - Z)R^2/(2\overline{W} + R)}{[2R + 4\overline{W}R/(2\overline{W} + R)]T + 2R\,.\,2\overline{W}R/(2\overline{W} + R)}$$

$$= \frac{-(P + Q)}{(8\overline{W} + 2R)T/R + 8\overline{W}}$$

$$= \frac{-G}{2Y_p[1 + T/Y_p + T/R]} \quad \ldots \quad (17y)$$

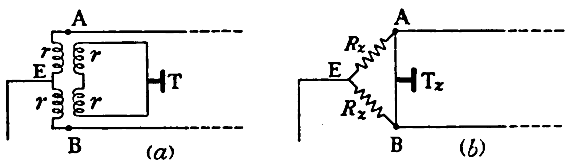


FIG. 17.—Transformer and equivalent resistances.

Case (*iii*). *Supply on phantom, listening on* CD, (+/CD).—By similarity,

$$\frac{V_2}{V_1} = \frac{-H}{2Y_2[1 + Y_p/R]\,[1 + R/(2Y_2) + T/Y_2]} \quad (18y)$$

Case (*iv*). *Supply on* CD, *listening on phantom*, (CD/+).

$$\frac{V_2}{V_1} = \frac{-H}{2Y_p[1 + T/Y_p + T/R]} \quad \ldots \quad (19y)$$

(*b*) When transformers are used, Fig. 17 (*a*) is equivalent to Fig. 17 (*b*).

Equating impedance to phantom currents,

$$\tfrac{1}{2}R_z = \tfrac{1}{2}r$$

Therefore $$R_z = r \quad \ldots \quad (20)$$

Equating impedance to side-circuit currents,

$$\frac{1}{2R_z} + \frac{1}{T_z} = \frac{1}{4r + Z_t} \quad \ldots \quad (21)$$

Case (*i*). *Supply on phantom, listening on* AB, (+/AB).—Substituting (20) and (21) in equation (16*z*),

$$\frac{V_2}{V_1} = \frac{-Z_1G}{2[1 + r/Z_p]\,[1 + Z_1/(4r + Z_t)]} \quad . \quad (22z)$$

Current in telephone,

$$I_t = \frac{V_2}{4r + Z_t}$$

$$\therefore\ I_t = \frac{-Z_1Z_p}{(Z_p + r)\,(Z_1 + 4r + Z_t)} \cdot \frac{G}{2}V_1 \quad . \quad (23z)$$

Case (*ii*). *Supply on side* AB, *listening on phantom*, (AB/+).—The voltage across the cable is less than that applied in the ratio $Z_1/(Z_1 + 4r)$, due to the drop in the transformer.

Equation (17) becomes, in impedances,

$$V_2 = \frac{-Z_p}{\left(1 + \dfrac{Z_p}{Z_t} + \dfrac{r}{Z_t}\right)} \cdot \frac{Z_1}{Z_1 + 4r} \cdot \frac{G}{2} \quad . \quad (24z)$$

Current in telephones,

$$I_t = \frac{V_2}{Z_t}$$

$$= \frac{-Z_1Z_p}{(Z_p + r + Z_t)\,(Z_1 + 4r)} \cdot \frac{G}{2}V_1 \quad . \quad (25z)$$

Cases (*iii*) *and* (*iv*).—The equations for +/CD and CD/+ are the same as (22) to (25), but H is written for G and Z_2 for Z_1.

(v) *Deductions from equations.*

(*a*) The interference between the physical circuits AB and CD is directly proportional to $\tfrac{1}{4}F$; $\tfrac{1}{4}F$ will be called the cross-talk coefficient of the quad ABCD.

(*b*) The interference between the phantom and the side circuits AB, CD is directly proportional to $-\tfrac{1}{2}G$ and $-\tfrac{1}{2}H$ respectively; $-\tfrac{1}{2}G$ and $-\tfrac{1}{2}H$ will be called the relevant overhearing coefficients of the AB and CD pairs, respectively.

(*c*) The formulæ given apply whether the distant end be open, closed or terminated in any manner; the required modifications are obtained by inserting the appropriate values of Y_s and Y_p or Z_s and Z_p.

(*d*) The formulæ can be extended to interference between quads by considering each group of wires acting in parallel as a single wire.

(*e*) The induced currents and voltages depend not only on the values of the interference coefficients and the circuit impedances, which are properties of the line, but also on the impedances of the transformers and telephones, i.e. on the external apparatus. This fact is often forgotten in making comparisons between the figures for different cables, and misleading deductions may be drawn.

(vi) *Quantitative definition of interference.*—In order to eliminate the effect of the external apparatus, we may define the interference Ψ as the ratio of the

power in the disturbed to that in the disturbing circuit, when the lines are closed by ideal transformers having no losses, and the impedance of the telephone is equal to that of the disturbed circuit.

Writing J for the general interference coefficient ($+\frac{1}{2}F$, $-\frac{1}{2}G$ or $-\frac{1}{2}H$) we see that all the equations reduce to the form

$$\frac{I_2}{I_1} = \frac{JZ_1}{2}$$

$$\frac{V_2}{V_1} = \frac{JZ_2}{2}$$

the suffixes 2 and 1 referring to the disturbed and disturbing circuits respectively. Therefore the interference

$$\Psi = \frac{P_2}{P_1} = \frac{J^2Z_1Z_2}{4} \quad . \quad . \quad . \quad . \quad (26)$$

It is often more convenient to use a ratio of currents (or voltages) to measure interference. To obtain a consistent result, we may write

$$\psi = (\sqrt{\Psi} = \tfrac{1}{2}J\sqrt{(Z_1Z_2)} \quad . \quad . \quad . \quad (27)$$

Here ψ is the interference expressed on a current (or voltage) ratio basis.

(vii) *Units.*—There are a number of systems of units in use at present in which interference is expressed.

(a) The one which appertains logically to the definition given above is the new transmission unit (T.U.) * which is based on a power ratio and is defined by

$$\text{T.U.} = 10 \log_{10} P_1/P_2$$

Thus

$$\text{T.U.} = 10 \log_{10} \frac{1}{\Psi} = 10 \log_{10} \frac{4}{J^2Z_1Z_2} \quad . \quad (28)$$

(b) The βl unit, which is expressed by the relation

$$\beta l = \log_e \frac{I_1}{I_2}$$

Thus

$$\beta l = \log_e \frac{1}{\psi} = \log_e \frac{2}{J\sqrt{(Z_1Z_2)}} \quad . \quad . \quad (29)$$

(c) The mile of standard cable (M.S.C.), given by

$$\text{M.S.C.} = \frac{1}{0{\cdot}1065} \log_e \frac{I_1}{I_2}$$

Thus

$$\text{M.S.C.} = 9{\cdot}38 \log_e \frac{1}{\psi} = 9{\cdot}38 \log_e \frac{2}{J\sqrt{(Z_1Z_2)}} \quad (30)$$

(d) The cross-talk meter unit, which is the ratio of induced to inducing current in millionths, i.e. if n is the cross-talk meter reading,

$$n = \frac{I_2}{I_1} \times 10^6$$

Thus $\quad n = \psi \times 10^6 = \frac{1}{2}J_1\sqrt{(Z_1Z_2)} \times 10^6$

As it is generally used, the cross-talk meter does not give this value directly; the question is more fully discussed in a later Section.

* R. V. L. HARTLEY: *Electrician*, 1925, vol. 94, pp. 55, 58 and 93.

Section 4. RELATION BETWEEN UNBALANCES IN THE LINE CONSTANTS AND THE INTERFERENCE COEFFICIENTS.

The equations obtained in the previous Section enable us to calculate the value of the individual currents and voltages when the interference coefficients are known. We must now investigate how the interference coefficients depend on the original causes, viz. the unbalances in the constants of the line, and we shall consider capacity, leakance, self-inductance, resistance and mutual inductance. The problem falls into two parts, viz. when the unbalance is very close to the measuring end, and when it is at a distance.

(A) *When the unbalance is very close to the measuring end.*

(i) *Unbalanced capacity.*—Since the unbalances are very close to the end, it follows from the definition of the interference coefficients that their relation to the unbalanced capacity is the same however the line is terminated; we can therefore consider the case of the

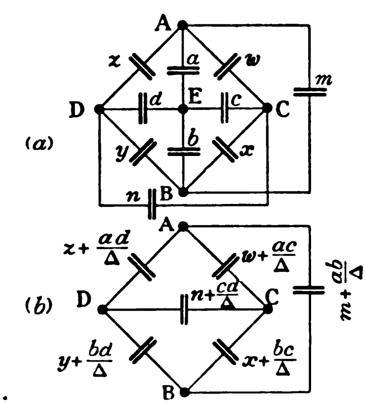


FIG. 18.—Capacity unbalance.

short length in which the distant end is free, and represent the capacity system by a network of condensers. Fig. 18 (a) shows a quad ABCD, and E represents the sheath which is earthed. By means of the four-ray star-mesh transformation, the point E can be eliminated, the resulting system being shown in Fig. 18 (b).

Then

$$P = j\omega\left\{w - x + \frac{c}{\Delta}(a - b)\right\}$$

$$Q = j\omega\left\{z - y + \frac{d}{\Delta}(a - b)\right\}$$

$$R = j\omega\left\{w - z + \frac{a}{\Delta}(c - d)\right\}$$

$$S = j\omega\left\{x - y + \frac{b}{\Delta}(c - d)\right\}$$

where $\quad \Delta = a + b + c + d$

Writing

$$w - x = p\,; \quad x - y = s$$
$$z - y = q\,; \quad a - b = u$$
$$w - z = r\,; \quad c - d = v$$

we obtain

$$F = j\omega\left(p - q + \frac{uv}{\Delta}\right) \quad . \quad . \quad . \quad (32)$$

$$G = j\omega\left(p + q + \frac{c+d}{\Delta}u\right) . \quad . \quad . \quad (33)$$

$$H = j\omega\left(r + s + \frac{a+b}{\Delta}v\right) . \quad . \quad . \quad (34)$$

Generally uv/Δ can be neglected compared with $p - q$, and $\frac{c+d}{\Delta} \simeq \frac{a+b}{\Delta} \simeq \frac{1}{2}$.

Therefore

$$F = j\omega(p - q) \quad . \quad . \quad . \quad . \quad (35)$$

$$G = j\omega(p + q + \tfrac{1}{2}u) . \quad . \quad . \quad . \quad (36)$$

$$H = j\omega(r + s + \tfrac{1}{2}v) . \quad . \quad . \quad . \quad (37)$$

$2(p + q) + u$ and $2(r + s) + v$ are known as the composite values of the AB and CD loops respectively.

(ii) *Unbalanced leakance.*—The system of leakances of a quad is the same as that of the capacities, and the corresponding equations are of a similar form. The

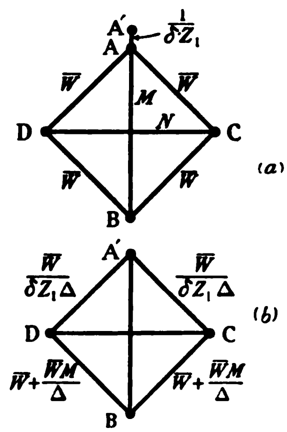


FIG. 19.—Impedance unbalance.

normal leakance of a telephone cable is of the order $G/(\omega C) = 1/250$, and thus the interference due to unbalanced leakance is, on the whole, only 1/250th of that due to capacity and in practice is negligibly small.

(iii) *Unbalanced self-inductance and resistance.*—Considering the AB pair, let the unbalance be in the A wire and equal in impedance to $\delta Z_1 = \delta r_1 + j\omega\delta l_1$. Since it is very close to the measuring end it must of necessity be small and can be represented by AA′ in Fig. 19 (*a*), the rest of the quad being shown by the equivalent network in the usual way. As we are dealing with admittances, $AA' = 1/(\delta Z_1)$. Transforming the four-ray star A′A, CA, BA, DA, we obtain Fig. 19 (*b*).

Then

$$A'C = \frac{\overline{W}}{\delta Z_1 \Delta}$$

$$BC = \overline{W} + \frac{\overline{W}M}{\Delta}$$

$$BD = \overline{W} + \frac{\overline{W}M}{\Delta}$$

$$A'D = \frac{\overline{W}}{\delta Z_1 \Delta}$$

where $\Delta = 2\overline{W} + M + 1/(\delta Z_1)$

Then

$$F = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

$$H = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

$$G = \frac{2\overline{W}}{\delta Z_1 \Delta} - 2\left(\overline{W} + \frac{\overline{W}M}{\Delta}\right)$$

$$= \frac{2\overline{W}}{\Delta}\left(\frac{1}{\delta Z_1} - \Delta - M\right)$$

$$= \frac{-4\overline{W}(\overline{W} + M)\delta Z_1}{1 + \delta Z_1(2\overline{W} + M)}$$

Since δZ_1 is very small, $\delta Z_1(2\overline{W} + M)$ can be neglected compared with unity. Substituting Y_p for $4\overline{W}$ and Y_1 for $\overline{W} + M$, we obtain

$$G = -Y_p Y_1 \delta Z_1 \quad . \quad . \quad . \quad . \quad (40)$$

Similarly if there is an unbalance δZ_2 in the CD pair,

$$H = -Y_p Y_2 \delta Z_2 \quad . \quad . \quad . \quad . \quad (41)$$

In a loaded cable with the distant end terminated Y_p, Y_1 and Y_2 are vectors with a small angle and are approximately independent of frequency.

If $\qquad G = g_1 + j\omega c_1$

then

$$g_1 = -Y_p Y_1 \delta r_1 \quad . \quad . \quad . \quad . \quad (42)$$

$$c_1 = -Y_p Y_1 \delta l_1 \quad . \quad . \quad . \quad . \quad (43)$$

these relations being approximately true for all frequencies. Similar equations apply to the CD pair.

We conclude from these equations that unbalanced

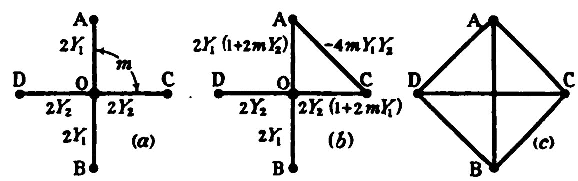


FIG. 20.—Mutual impedance unbalance.

self-impedance has no direct influence in causing cross-talk, and that it affects the overhearing only in the pair in which it occurs. In a loaded cable, provided the line is long or is suitably terminated, unbalanced series resistance and inductance are approximately equivalent to and can be compensated by shunt leakance and capacity respectively.

Example.—If $Y_s = 1/450$ mho, $Y_p = 1/190$ mho.

$$Y_p Y_s = 11 \cdot 7 \times 10^{-6}$$

Then $\qquad g = 11 \cdot 7$ micro-mhos per ohm

$$c = -11 \cdot 7 \ \mu\mu\text{F per } \mu\text{H}$$

(iv) *Unbalanced mutual inductance.*—In practice, mutual inductance unbalance is ignored and it would appear that its effect is very small. It is, nevertheless, desirable to see if this supposition is correct, and we shall take the case in which the phantom impedance is half the mean of the side circuits, so that the equivalent network is a four-ray star. Let there be an unbalanced mutual impedance between arms OA, OC equal to m, Fig. 20 (*a*). This can be transformed into Fig. 20 (*b*)

(see Appendix II), and then as a four-ray star into Fig. 20 (*c*).

In Fig. 20 (*a*), if Y_1, Y_2 are the admittances of the AB and CD loops respectively, then

$$\mathrm{OA} = \mathrm{OB} = 2Y_1 \quad \text{and} \quad \mathrm{OC} = \mathrm{OD} = 2Y_2$$

In Fig. 20 (*b*)

$$\mathrm{OA} = 2Y_1(1 + 2mY_2)$$
$$\mathrm{OC} = 2Y_2(1 + 2mY_1)$$
$$\mathrm{AC} = -\,4mY_1Y_2$$

and OB, OD are unaltered.

In Fig. 20 (*c*)

$$\mathrm{AC} = -\,4mY_1Y_2 + \frac{4Y_1Y_2(1 + 2mY_1)\,(1 + 2mY_2)}{\Delta}$$

where $\Delta = 4Y_1 + 4Y_2 + 8mY_1Y_2$

i.e. $$\mathrm{AC} = \frac{4Y_1Y_2}{\Delta}(1 - 2mY_1 - 2mY_2 - 4m^2Y_1Y_2)$$

$$\mathrm{BC} = \frac{4Y_1Y_2}{\Delta}(1 + 2mY_1)$$

$$\mathrm{AD} = \frac{4Y_1Y_2}{\Delta}(1 + 2mY_2)$$

$$\mathrm{BD} = \frac{4Y_1Y_2}{\Delta}$$

$$\therefore P = \frac{-\,4Y_1Y_2}{\Delta}(4mY_1 + 2mY_2 + 4m^2Y_1Y_2)$$

$$Q = \frac{4Y_1Y_2}{\Delta}2mY_2$$

$$R = \frac{-\,4Y_1Y_2}{\Delta}(2mY_1 + 4mY_2 + 4m^2Y_1Y_2)$$

$$S = \frac{4Y_1Y_2}{\Delta}2mY_1$$

Since the unbalance is all located at the near end of the line, it must be very small, and thus m^2 can be neglected compared with m, and $\Delta = 4Y_1 + 4Y_2$.

$$\therefore F = \frac{-\,4Y_1Y_2}{4Y_1 + 4Y_2}(4mY_1 + 4mY_2)$$
$$= -\,4Y_1Y_2m \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

$$G = \frac{-\,4Y_1Y_2}{4Y_1 + 4Y_2}4mY_1$$
$$= -\,Y_1Y_pm \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

$$H = -\,Y_2Y_pm \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

If the mutual inductance $= M$, then $m = j\omega M$, i.e.

$$F = -\,4j\omega Y_1Y_2M \quad . \quad . \quad . \quad . \quad (47)$$

etc.

As with self-inductance, if the cable is loaded and the line is terminated, Y_1, Y_2 and Y_p are vectors of small angle, and approximately independent of frequency.

Thus
$$\left.\begin{aligned} c &= -\,4Y_1Y_2M \\ c_1 &= -\,Y_1Y_2M \\ c_2 &= -\,Y_1Y_pM \end{aligned}\right\} \quad . \quad . \quad . \quad (48)$$

where c, c_1, c_2 are the capacity components of F, G and H respectively.

Therefore, in a long loaded line, mutual inductance is equivalent to, and can be compensated by, shunt capacity.

That mutual inductance does not appear to have any effect on interference is due to a variety of reasons. In a cable with unloaded cores it depends on the geometrical disposition of the conductors in the same way as does the capacity, if the dielectric be uniform, so that when the capacity is balanced by crossing the cores (q.v.) the unbalanced mutual inductance is reduced at the same time. In a continuously loaded cable, as regards overhearing, the form of the equations is the same as for self-inductance unbalance, and where the latter is measured and compensated the unbalanced mutual inductance will be included. As regards cross-talk, it can be shown that the effect due to mutual inductance is but little dependent on normal variations in the thickness or permeability of the iron covering the conductors; e.g. if core A has a higher permeability, it will increase both M_{ac} and M_{ad}, and the effect on the cross-talk, which is due to the difference between these increases, will be small. Consequently, unbalanced mutual inductance, as affecting cross-talk, depends mainly on the geometrical arrangement of the cores and will be balanced out with the capacity. Where, however, there is no direct capacity between the cores owing to the presence of a conducting screen between them, we may expect mutual inductance to be noticeable; this is the case with a submarine cable having gutta-percha as dielectric, as the water has access to the spaces between the cores. In a recent example, the author found that there was a certain amount of cross-talk, although, as was to be expected, capacity unbalance measurements on short lengths with the distant end open showed that this was not due to electrostatic interference. When, however, the ends of these sections were terminated, and measurements were made with the bridge described in Section 6 (iii), the cross-talk coefficient was found to be appreciable, and steps had to be taken to reduce this as well as the overhearing coefficients.

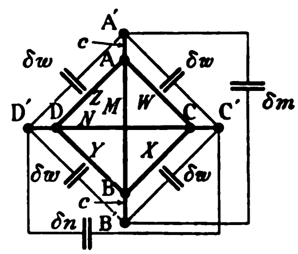


FIG. 21.

(B) *When the unbalance is some distance from the measuring end.*—We have now to determine how the interference coefficients are modified when the unbalance exists some distance from the measuring end.

Let ABCD (Fig. 21) represent a quad, the equivalent network having the values marked; and AA′, BB′, CC′, DD′ represent a further small section of similar line, free from unbalances, of length δl, placed in front of ABCD. Since this added length is very short, the distributed capacities and leakances may be replaced

by leaky condensers at the near end of the added portion, as shown in the diagram.

Let the interference coefficients of ABCD measured at ABCD be $\frac{1}{4}F$, $-\frac{1}{2}G$, $-\frac{1}{2}H$ respectively. We have to determine the change when measured at A′, B′, C′, D′ caused by the presence of the conductors AA′, BB′, CC′, DD′ each of admittance c; the admittances δw will obviously not alter the values of the coefficients. This can conveniently be done in two stages, AA′, BB′ being added first and CC′, DD′ later.

To eliminate points AB from the network in Fig. 22 (*a*), first the four-ray star A′A, CA, BA, DA is transformed into the corresponding mesh.

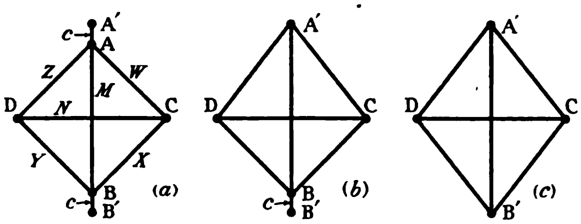


FIG. 22.

Let $W + M + Z + c = \Delta_1$.

Then in Fig. 22 (*b*),

$$A'C = \frac{Wc}{\Delta_1}$$

$$A'D = \frac{Zc}{\Delta_1}$$

$$A'B = \frac{Mc}{\Delta_1}$$

$$CD = M + \frac{WZ}{\Delta_1}$$

$$BC = X + \frac{WM}{\Delta_1}$$

$$BD = Y + \frac{ZM}{\Delta_1}$$

Secondly, the four-ray star B′B, CB, A′B, DB is transformed into the corresponding mesh.

Let $X + M + Y + c = \Delta_2$.

Then in Fig. 22 (*c*)

$$B'C = \frac{c(X + WM/\Delta_1)}{(M/\Delta_1)(W + Z + c) + X + Y + c}$$

$$= \frac{c(\Delta_1 X + WM)}{M(\Delta_1 - M) + \Delta_1(\Delta_2 - M)}$$

i.e.
$$B'C = \frac{c}{\Delta_1\Delta_2 - M^2}(\Delta_1 X + WM)$$

By symmetry

$$B'D = \frac{c}{\Delta_1\Delta_2 - M^2}(\Delta_1 Y + ZM)$$

$$A'C = \frac{c}{\Delta_1\Delta_2 - M^2}(\Delta_2 W + XM)$$

$$A'D = \frac{c}{\Delta_1\Delta_2 - M^2}(\Delta_2 Z + YM)$$

Since the conductors AA′, BB′ are short, the admittance c will be great; further $W \simeq X \simeq Y \simeq Z$.

Therefore we may write $\Delta_1 = \Delta_2 = \Delta$

where
$$\Delta = 2\overline{W} + M + c$$

Now

$$P' = A'C - B'C = \frac{c}{\Delta^2 - M^2}\{\Delta(W - X) + M(X - W)\}$$

$$= \frac{c}{\Delta^2 - M^2}(\Delta - M)P = \frac{c}{\Delta + M}P$$

$$Q' = A'D - B'D = \frac{c}{\Delta^2 - M^2}\{\Delta(Z - Y) + M(Y - Z)\}$$

$$= \frac{c}{\Delta + M}Q$$

$$R' = A'C - A'D = \frac{c}{\Delta^2 - M^2}\{\Delta(W - Z) + M(X - Y)\}$$

$$= \frac{c}{\Delta^2 - M^2}(\Delta R + MS)$$

$$S' = B'C - B'D = \frac{c}{\Delta^2 - M^2}\{\Delta(X - Y) + M(W - Z)\}$$

$$= \frac{c}{\Delta^2 - M^2}(\Delta S + MR)$$

$$\left.\begin{aligned} F' &= P' - Q' = \frac{c}{\Delta + M}F \\ G' &= P' + Q' = \frac{c}{\Delta + M}G \\ H' &= R' + S' = \frac{c}{\Delta - M}H \end{aligned}\right\} \quad . \quad . \quad (49)$$

Here we may notice that if a line have the following constants :—

Resistance, R ohms per unit length
Inductance, L henrys per unit length
Capacity, C farads per unit length
Leakance, G mhos per unit length

the line impedance $\quad Z = R + j\omega L$

the line admittance $\quad Y = G + j\omega C$

characteristic admittance $\quad Y_0 = \sqrt{\dfrac{Y}{Z}}$

propagation constant $\quad \gamma = \sqrt{(ZY)}$

Therefore $\quad \gamma = Y_0 Z$

For a length l $\quad \gamma l = Y_0 Z l$

Zl may be called the line impedance of the length l.

Reverting to the main argument

$$\frac{c}{\Delta + M} = \frac{c}{2\overline{W} + 2M + c} = \frac{1}{1 + 2Y_1/c}$$

If the quad considered be terminated, Y_1 becomes Y_{01}, the characteristic admittance of side circuit AB.

Further, $2/c$ is the line impedance of the side circuit AA′, BB′.

Therefore $\quad 2Y_{01}/c = \gamma_1 \delta l$

where γ_1 is the propagation constant per unit length of the side circuit AB.

Similarly $\dfrac{c}{\Delta - M} = \dfrac{c}{2\overline{W} + c} = \dfrac{1}{1 + Y_p/(2c)}$

$1/(2c)$ is the line impedance of the phantom circuit AA′, BB′ and, as the quad is terminated, Y_p becomes Y_{0p}.

Therefore $\qquad Y_{0p}/(2c) = \gamma_p \delta l$

where γ_p is the propagation constant per unit length of the phantom circuit.

Therefore
$$F' = \frac{1}{1 + \gamma_1 \delta l} F$$
$$G' = \frac{1}{1 + \gamma_1 \delta l} G$$
$$H' = \frac{1}{1 + \gamma_p \delta l} H$$

Adding the short conductors CC′, DD′, the corresponding factors will be :—

for F', $\qquad \dfrac{1}{1 + \gamma_2 \delta l}$

for G', $\qquad \dfrac{1}{1 + \gamma_p \delta l}$

for H', $\qquad \dfrac{1}{1 + \gamma_2 \delta l}$

Thus, when the four wires are added, the combined result is

$$\left.\begin{aligned} F' &= \left(\frac{1}{1 + \gamma_1 \delta l}\right)\left(\frac{1}{1 + \gamma_2 \delta l}\right) F \\ G' &= \left(\frac{1}{1 + \gamma_1 \delta l}\right)\left(\frac{1}{1 + \gamma_p \delta l}\right) G \\ H' &= \left(\frac{1}{1 + \gamma_2 \delta l}\right)\left(\frac{1}{1 + \gamma_p \delta l}\right) H \end{aligned}\right\} \quad . \quad . \quad (50)$$

Now, if the added section be of any length l, let it be divided into n small parts, where n is a large number. Then

$$F' = \left\{\frac{1}{1 + \gamma_1 (l/n)}\right\}^n \left\{\frac{1}{1 + \gamma_2 (l/n)}\right\}^n F$$

When n becomes infinitely great,

$$\left\{\frac{1}{1 + \gamma_1 (l/n)}\right\}^n \text{ becomes } e^{-\gamma_1}$$

where e is the base of natural logarithms.

i.e. $$F' = e^{-(\gamma_1 + \gamma_2)l} F \quad . \quad . \quad . \quad . \quad (51)$$

Similarly $$G' = e^{-(\gamma_1 + \gamma_p)l} G \quad . \quad . \quad . \quad . \quad (52)$$

$$H' = e^{-(\gamma_2 + \gamma_p)l} H \quad . \quad . \quad . \quad . \quad (53)$$

We can obtain an idea of the physical meaning of these equations by considering Fig. 23, in which the line is looked at along its length. The source at AB sends a wave of current along circuit 1, which when it has travelled a distance l has been attenuated by a factor $e^{-\gamma_1 l}$. At this point there is an unbalance which gives rise to an induced voltage in circuit 2, and the wave of induced current in travelling back to the detector at CD is attenuated by a further factor $e^{-\gamma_2 l}$. This aspect, however, is complicated by, among other things, the impedance of the receiver. The method of equivalent networks introduces no assumptions in that respect, and as the interference coefficients are, by definition, admittance operators, they are independent of the apparatus external to the sending end of the line and are the same however measured.

In the foregoing discussion it was stated that the section of line placed in front of ABCD was free from unbalances. If, however, it itself possesses interference coefficients $\frac{1}{4}F_1$, $-\frac{1}{2}G_1$, $-\frac{1}{2}H_1$, when measured from A′B′C′D′ and terminated at its distant end, these may be regarded as being produced by small admittances parallel with the arms A′C′, C′B′, B′D′, D′A′, and thus the effective interference coefficients are the result of

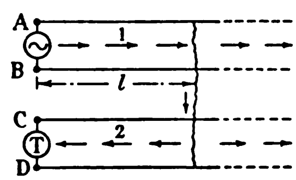


FIG. 23.

admittances in parallel and are added algebraically. In this case,

$$F' = F_1 + Fe^{-(\gamma_1+\gamma_2)l} \quad . \quad . \quad . \quad (54)$$
$$G' = G_1 + Ge^{-(\gamma_1+\gamma_p)l} \quad . \quad . \quad . \quad (55)$$
$$H' = H_1 + He^{-(\gamma_2+\gamma_p)l} \quad . \quad . \quad . \quad (56)$$

We may generalize this in the following statement :—

If we have a number of sections of similar line, 1, 2, 3, . . . connected in series in that order, each of which when measured at its nearer end and terminated at its further end has interference coefficients $\frac{1}{4}F_1$, $-\frac{1}{2}G_1$, $-\frac{1}{2}H_1$; $\frac{1}{4}F_2$, $-\frac{1}{2}G_2$, $-\frac{1}{2}H_2$; $\frac{1}{4}F_3$, $-\frac{1}{2}G_3$, $-\frac{1}{2}H_3$; . . . respectively, and if the beginnings of the sections are at distances $l_1 (= 0)$, l_2, l_3, . . . respectively from the near end of the line, the resultant interference coefficients $\frac{1}{2}F'$, $-\frac{1}{2}G'$, $-\frac{1}{2}H'$ measured at this near end with the distant end terminated will be such that :—

$$F' = F_1 + F_2 e^{-(\gamma_1+\gamma_2)l_2} + F_3 e^{-(\gamma_1+\gamma_2)l_3} + \; . \quad (57)$$
$$G' = G_1 + G_2 e^{-(\gamma_1+\gamma_p)l_2} + G_3 e^{-(\gamma_1+\gamma_p)l_3} + \; . \quad (58)$$
$$H' = H_1 + H_2 e^{-(\gamma_2+\gamma_p)l_2} + H_3 e^{-(\gamma_2+\gamma_p)l_3} + \; . \quad (59)$$

Section 5. VARIATION OF THE INTERFERENCE COEFFICIENTS WITH FREQUENCY.

(i) *When the unbalance is close to the measuring end.*—It has been shown that as regards unbalances on a long loaded line, mutual and self-inductance are equivalent to capacity, and resistance to leakance.

The effective leakance component of an interference coefficient consists of :—

(i) True leakance, which varies approximately as the

first power of the frequency; this is generally negligibly small.

(ii) Resistance, viz. (*a*) d.c. resistance, which is independent of frequency, (*b*) a.c. losses consisting of eddy-current losses which vary as the square of the frequency, and, in a loaded line, hysteresis losses which vary as the first power of the frequency.

Generally the effective leakance component is comparatively small in a loaded line. (An exception may arise when there is a high-resistance joint in a conductor, in which case there will be a large d.c. unbalance independent of frequency.) In the cross-talk coefficient it is in any case negligible, being due only to true leakance.

The effective capacity component may be due to (i) true capacity, (ii) mutual inductance, (iii) self-inductance, all three of which are independent of frequency. In the cross-talk coefficient only capacity and mutual inductance play a part.

Summing up, the capacity component, which is the principal, is independent of frequency; the leakance component in cross-talk is negligibly small, in over-hearing it is also small and is independent of frequency if due to d.c. resistance, and varies as some power between the first and second if due to a.c. losses.

(ii) *When the unbalance is some distance from the measuring end.*—As equations (57), (58) and (59) are of the same type, they may be written in the general form:—

$$J' = \Sigma(J_n e^{-2\gamma l_n}) \quad . \quad . \quad . \quad . \quad (60)$$

where J_n is the value of the interference coefficient of the nth section as measured from its nearer end with its further end terminated,

J' is the interference coefficient as measured at the near end of the line, with the distant end terminated,

l_n is the distance of the beginning of the nth section from the near end of the line,

γ is the average of the propagation constants of the two circuits,

β is the average of the attenuation constants,

and α is the average of the wave-length constants.

Then $$J' = \Sigma(J_n e^{-2\beta l_n}) \overline{\rfloor 2\alpha l_n} \quad . \quad . \quad . \quad (61)$$

i.e. each term is reduced by its appropriate factor $e^{-2\beta l_n}$ and its phase is shifted backwards by the angle $2\alpha l_n$.

Writing $J_n = g_n + j\omega c_n$, and $J' = g' + j\omega c'$, we have

$$J' = \Sigma\{(g_n + j\omega c_n)e^{-2(\beta + j\alpha)l_n}\}$$

i.e.

$$g' + j\omega c' = \Sigma\{(g_n + j\omega c_n)(\cos 2\alpha l_n - j \sin 2\alpha l_n)e^{-2\beta l_n}\}$$

$$\therefore g' = \Sigma\{(g_n \cos 2\alpha l_n + \omega c_n \sin 2\alpha l_n)e^{-2\beta l_n}\} \quad (62)$$

and $$c' = \Sigma\{(\omega c_n \cos 2\alpha l_n - g_n \sin 2\alpha l_n)e^{-2\beta l_n}\}. \quad (63)$$

If the terms g_n are small enough to be neglected,

$$g' = \omega\Sigma(c_n \sin 2\alpha l_n e^{-2\beta l_n}) \quad . \quad . \quad . \quad (64)$$

$$\omega c' = \omega\Sigma(c_n \cos 2\alpha l_n e^{-2\beta l_n}) \quad . \quad . \quad . \quad (65)$$

In a loaded line, $\alpha = \frac{1}{2}\omega\{\sqrt{(C_1 L_1)} + \sqrt{(C_2 L_2)}\}$ approx. $= \omega k$, where C_1, C_2 and L_1, L_2 are the capacities and inductances per unit length of the two circuits respectively.

Therefore

$$g' = \omega\Sigma(c_n e^{-2\beta l_n} \sin 2\omega k l_n) \quad . \quad . \quad . \quad (66)$$

$$\omega c' = \omega\Sigma(c_n e^{-2\beta l_n} \cos 2\omega k l_n) \quad . \quad . \quad (67)$$

i.e. $$c' = \Sigma(c_n e^{-2\beta l_n} \cos 2\omega k l_n) \quad . \quad . \quad . \quad (68)$$

Thus each unbalance gives rise to a term periodic in ω, the value between successive peaks being $\omega = \pi/(kl_n)$ or

$$f = \frac{1}{2kl_n}$$

The further away the seat of the unbalance the closer together are the peaks in the frequency curve.

The resultant of several unbalances along the line will consist of the sum of a number of such curves, each of which has a different period in ω, and thus will present a complex appearance. The amplitudes of the total value $(g' + j\omega c')$ and also of g' will tend to increase with frequency on account of the term ω outside the bracket, while c' will tend to decrease slightly with frequency on account of the attenuation factors $e^{-\beta l_n}$, the terms c_n, as shown in the preceding Section, being independent of frequency.

If there be a particularly large unbalance at some point, the corresponding periodic curve will be well marked on plotting the interference coefficient against frequency, and this affords a means of locating its position. The factor k is easily obtained and thus the distance of the disturbance from the measuring end is

$$l = \frac{1}{2fk} \quad . \quad . \quad . \quad . \quad . \quad (69)$$

where f is the frequency interval in cycles per second between the peaks in the periodic curve.*

(iii) *Example.*—To illustrate how the interference coefficients vary with frequency, we may consider the cross-talk between two similar circuits; for simplicity the attenuation constant β for each circuit is taken as being 0·02 per mile for all frequencies, and the wave-length constant $\alpha = \omega/20\,000$. Let there be unbalances whose capacity components are $-300\ \mu\mu$F at the measuring end, $-1\,000\ \mu\mu$F at a distance of 5 miles and $+1\,000\ \mu\mu$F at a distance of 10 miles, the leakance components being zero. Equations (64) and (65) become

$$g = g_1 + g_2 + g_3 \quad . \quad . \quad . \quad . \quad (70)$$

where
$$g_1 = 0$$
$$g_2 = -1\,000e^{-0\cdot 2} \sin(\omega/2\,000)\omega$$
$$g_3 = +1\,000e^{-0\cdot 4} \sin(\omega/1\,000)\omega$$

and $$c = c_1 + c_2 + c_3 \quad . \quad . \quad . \quad . \quad (71)$$

where
$$c_1 = -300$$
$$c_2 = -1\,000e^{-0\cdot 2} \cos(\omega/2\,000)$$
$$c_3 = +1\,000e^{-0\cdot 4} \cos(\omega/1\,000)$$

In Fig. 24, the capacity components are plotted, c_1, c_2 and c_3 in broken lines, the total, c, in a full line; in Fig. 25 the leakance components are similarly treated.

* FERRIS and McCURDY: "Telephone Circuit Unbalances," *Journal of the American I.E.E.* 1924, vol. 43, p. 1133.

In Fig. 26 the modulus of the resultant [$= \sqrt{(g^2 + \omega^2 c^2)}$] is shown.

(iv) *Deductions.*—The equations obtained in this and the preceding Section show to what extent interference

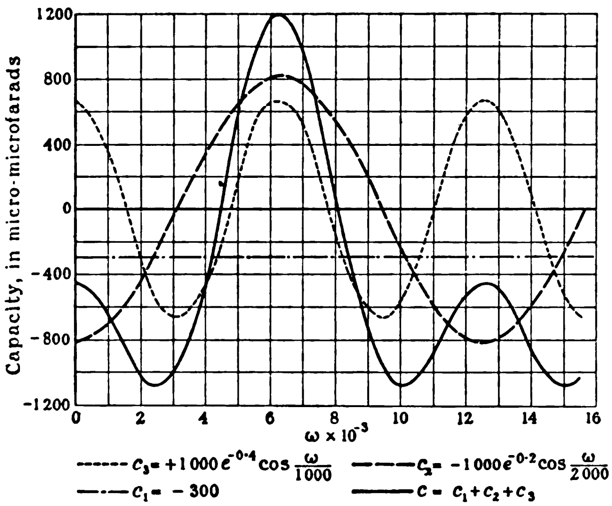


FIG. 24.—Variation of unbalance with frequency. Capacity component.

is caused by various factors and enable us to judge the effectiveness of the methods of reducing it.

Where no attempt is made to control them, the unbalances will occur in an arbitrary manner and, speaking generally, one would expect that, in a long line, for every unbalance there is somewhere along the length a similar unbalance of opposite sign. The extent

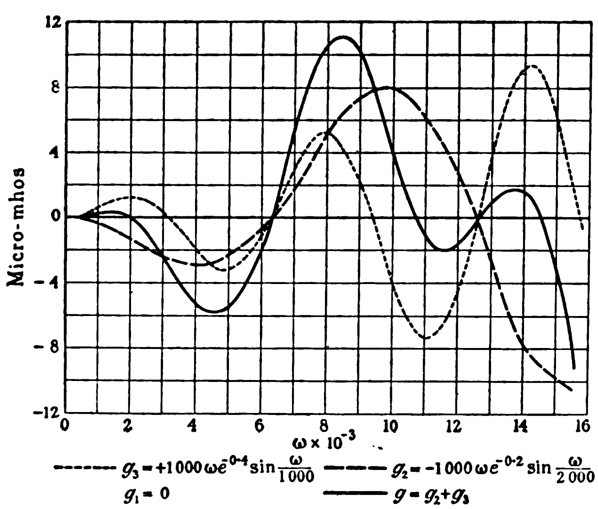


FIG. 25.—Variation of unbalance with frequency. Leakance component.

to which these will neutralize each other depends on the distance between them, the wave-length constant and, to a lesser degree, the attenuation constant. In the example given, the unbalances of + 1 000 and − 1 000 $\mu\mu$F separated by 5 miles do not cancel each other, in fact in the most important region of frequencies they add up. Where the inductance is high, interference would be increased, as not only would the inductance unbalances be higher, but the wave-length constant is large and the attenuation constant small. Thus one would expect interference to give more trouble on a loaded line, and this is a point in favour of lighter loading.

The equations also throw a light on the difficulties

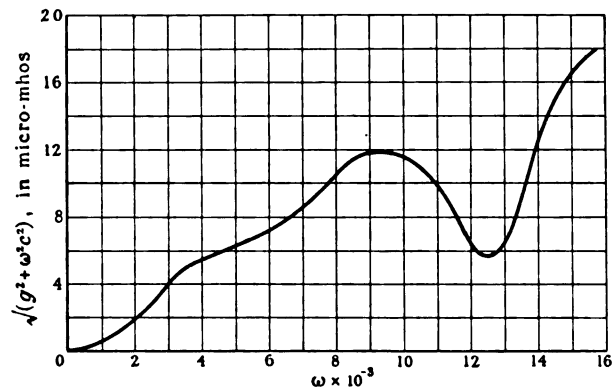


FIG. 26.—Variation of unbalance with frequency. Modulus of resultant.

in the measurement of interference, which forms the subject of the next Section.

Section 6. METHODS OF MEASUREMENT.

This subject as applied to interference is in itself a wide one, and for the most part only the outlines can be considered.

(i) *Unbalanced capacity.*—This is taken on sections short compared with the wave-length, with the distant end open, so that the distributed capacities may be regarded as replaced by lumped condensers of the same value.

P.O. double bridge.—The method developed by the British Post Office is illustrated in Fig. 27. R_1, R_2 are equal non-reactive resistances of 1 000 ohms each; K_1, K_2, variable air condensers having a maximum value of 1 200 $\mu\mu$F each; k_1, k_2, fixed air condensers each of value 600 $\mu\mu$F. Alternating current of frequency about 1 000 cycles per sec. is supplied through a screened

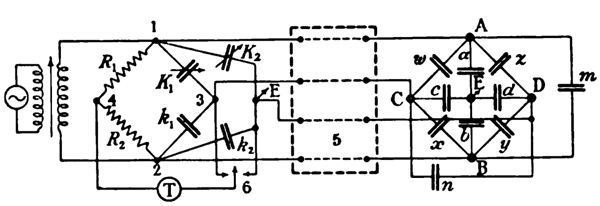


FIG. 27.—Unbalanced capacity bridge.

and balanced transformer to the corners 1, 2. The quad is connected to the bridge through a switch 5 (not shown in detail) which has 4 positions. In the first, or " P " position, A is joined to 1, B to 2, C to 3 and D to earth (E). By means of switch 6, the telephone is connected between 4 and C, and the wire-

to-wire condenser K_1 is varied until silence is obtained. Switch 6 is then thrown over so that the telephone is connected between 4 and E and the wire-to-earth condenser, K_2, adjusted for balance. On switching back to C, K_1 is re-adjusted and the cycle is repeated, each time coming closer to the true balance until finally silence is obtained in both positions. In these circumstances

$$K_1 + w = k_1 + x$$

i.e.
$$k_1 - K_1 = w - x = p \quad . \quad . \quad . \quad (72)$$

and
$$K_2 + z + a = k_2 + y + b$$

i.e.
$$\begin{aligned} k_2 - K_2 &= z - y + a - b \\ &= u + q = p_e \quad . \quad . \quad . \quad (73) \end{aligned}$$

The variable condensers are calibrated from + 600 to − 600 $\mu\mu$F so as to read $k_1 - K_1$ and $k_2 - K_2$ directly. On changing the switch 5 to the "Q" position, D is connected to 3 and C to E, A and B remaining unaltered. The readings of the wire-to-wire and wire-to-earth condensers after balance has been obtained give q and $q_e = u + p$ respectively. In the third or "R" position, C is joined to 1, D to 2, A to 3 and B to E, and one obtains r and $r_e = v + s$. Finally in

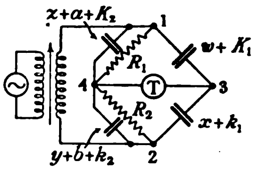


Fig. 28.

the "S" position, B is connected to 3 and A to E, C and D remaining unaltered, and the condenser readings give s and $s_e = v + r$, respectively. From these eight readings one obtains

$$p - q = r - s,$$
$$p + q, \quad r + s,$$
$$p_e - q = q_e - p = u,$$
$$r_e - s = s_e - r = v.$$

The duplications provided by the cross-talk and the earth figures afford an immediate check on the accuracy of the readings.

A considerable saving of time is effected if, when the switch 6 is in the "wire-to-wire" position, i.e. connecting the telephone between 4 and 3, the point 4 is put to earth. The resulting bridge network for the "P" position is shown in Fig. 28, the capacities shunting the source and detector being omitted. The conditions for balance are

$$\left.\begin{aligned} K_1 + w &= k_1 + x \\ \text{and} \quad K_2 + z + a &= k_2 + b + y \end{aligned}\right\} \quad . \quad . \quad (74)$$

The second condition is affected by the leakance of the cable and is not reliable; the first, however, gives the required setting of the wire-to-wire condenser in one operation and the corresponding wire-to-earth balance is then obtained as previously, necessitating only one further operation.

Other methods have been developed, notably by the Western Electric Co. (British Patent, Specification No. 203870), and a single-bridge arrangement is described by E. A. Beavis in an article on "Trunk Telephone Cables." [*]

(ii) *Unbalanced inductance and resistance.*—This is likewise taken on sections short compared with the wave-length; the distant end is short-circuited, so that the cores can be represented by lumped inductances and resistances. A form of bridge suitable for measuring these unbalances is shown in Fig. 29. R_1 and R_2 are equal non-reactive resistances of 100 or 1 000 ohms each; L_1 and L are variable and fixed inductances

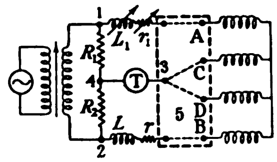


Fig. 29.

respectively, r_1 and r, variable and fixed resistances respectively. The current is supplied through a screened and balanced transformer to the points 1, 2, the telephone being connected between 3 and 4. The quad is connected to the bridge through the switch 5 which has two positions. In the first A is connected to the variable arm, B to the fixed arm, C and D to 3. When L_1 and r_1 are adjusted for balance,

$$r_1 + j\omega L_1 + r_a + j\omega L_a = r + j\omega L + r_b + j\omega L_b$$

$$\left.\begin{aligned} \text{i.e.} \quad r - r_1 &= r_a - r_b = r_{ab} \\ \text{and} \quad L - L_1 &= L_a - L_b = l_{ab} \end{aligned}\right\} \quad . \quad . \quad . \quad (75)$$

The adjustable resistance and inductance are calibrated to read $r - r_1$ and $L - L_1$ respectively. In

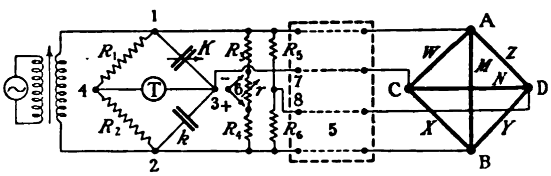


Fig. 30.—Measurement of interference coefficients.

the second position of 5, C is connected to the variable arm, D to the fixed arm, A and B to 3, and the unbalanced resistance and inductance of the CD pair are obtained.

(iii) *Measurement of interference coefficients.* — The interference coefficients as defined in Section 3 are admittance operators, and can be taken on a bridge which measures both unbalanced capacity and unbalanced leakance. The form used by the author [†] is shown in Fig. 30.

R_1 and R_2 are equal non-reactive resistances of 1 000 ohms each, K a variable air condenser of maximum value 1 200 $\mu\mu$F, k a fixed air condenser of 600 $\mu\mu$F, R_3 and R_4 equal non-reactive resistances of 10 000 ohms

[*] *Electrician*, 1924, vol. 92, p. 318.
[†] British Patent Specification No. 241972.

each, r a 3-dial variable non-reactive resistance of maximum value 1 000 ohms, R_5 and R_6 equal non-reactive resistances of 100 ohms each. R_3 and R_4 are in parallel with K, k respectively, and, by means of switch 6, r is put in series with either R_3 or R_4. Switch 5 is a "PQRS" switch as described in Sub-section (i), and connects the quad ABCD, which is here represented by its equivalent network, to the bridge.

Neglecting for the time being the resistances R_5 and R_6, the conditions for balance (in the "P" position) may be obtained as follows:—Transform the star AD, CD, BD into its mesh. Then AC becomes

$$W + \frac{NZ}{Z + Y + N} = W + \lambda_1 Z$$

and BC becomes

$$X + \frac{NY}{Z + Y + N} = X + \lambda_1 Y$$

where $$\lambda_1 = \frac{N}{Z + Y + N}$$

Assuming that switch 6 is the + position, i.e. r is in series with R_3,

$$\frac{1}{r + R_3} + j\omega K + W + \lambda_1 Z = \frac{1}{R_4} + j\omega k + X + \lambda_1 Y$$

i.e. $$\frac{r}{10\,000\,(10\,000 + r)} + j\omega(k - K) = P + \lambda_1 Q$$

If r is small, it may be neglected compared with 10 000 ohms; also the variable condenser is calibrated to read $k - K = c$ directly. Thus we may write

$$10^{-8} r_p + j\omega c_p = P + \lambda_1 Q \quad . \quad . \quad . \quad (76)$$

the p suffix denoting readings in the "P" position. Similarly, in the "Q" position

$$10^{-8} r_q + j\omega c_q = Q + \lambda_2 P \quad . \quad . \quad . \quad (77)$$

where $$\lambda_2 = \frac{N}{W + X + N}$$

Now $\lambda_1 \simeq \lambda_2 \simeq \lambda$, where $\lambda = N/(2\overline{W} + N)$

$$\therefore\ (r_p - r_q)10^{-8} + j\omega(c_p - c_q) = (1 - \lambda)\,(P - Q) = (1 - \lambda)F \quad . \quad (78)$$

and

$$(r_p + r_q)10^{-8} + j\omega(c_p + c_q) = (1 + \lambda)\,(P + Q) = (1 + \lambda)G \quad . \quad (79)$$

From the "R" and "S" positions, we obtain

$$(r_r + r_s)10^{-8} + j\omega(c_r + c_s) = (1 + \lambda')H \quad . \quad (80)$$

and $$(r_r - r_s)10^{-8} + j\omega(c_r - c_s) = (1 - \lambda')F \quad . \quad (81)$$

where $$\lambda' = M/(2\overline{W} + M)$$

Nearly always the quad is a symmetrical one, i.e. the pairs AB and CD are alike; then $\lambda = \lambda'$, and equation (81) gives a check on the accuracy of the readings.

The effect of the 100-ohm resistance is to reduce λ to $\dfrac{\overline{M}}{2\overline{W} + \overline{M} + (2/100)}$, and thus variations in λ_1, λ_2 are of less account. For example, if $\overline{M} = 1/1\,100$ mho, $\overline{W} = 1/760$ mho, without the 100-ohm resistances $\lambda = 0{\cdot}257$, whereas with the 100-ohm resistances $\lambda = 0{\cdot}039$.

If only the overhearing coefficients are required, points 7 and 8 are joined, the 100-ohm resistances being omitted. The "P" (or "Q") position gives G directly, and the "R" (or "S") position gives H directly.

Series inductance method.—It has been shown that, as regards overhearing, series inductance and resistance are equivalent to shunt capacity and leakance respectively. Hence the bridge described in Sub-section (ii) for measuring inductance and resistance unbalances can be used for obtaining the overhearing coefficients, the relations being

$$\left.\begin{aligned} G &= -\,Y_1 Y_p(r_{ab} + j\omega l_{ab}) \\ H &= -\,Y_2 Y_p(r_{cd} + j\omega l_{cd}) \end{aligned}\right\} \quad . \quad . \quad . \quad (82)$$

The series method is of advantage where the impedance of the line is low, e.g. a fairly short length

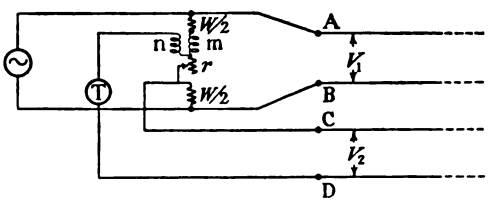


FIG. 31.—Measurement of induced voltage.

with the distant end short-circuited, but it does not give the cross-talk coefficient. This type of bridge has been used by Ferris and McCurdy for locating irregularities in transmission lines, as described in Section 5 (ii).

(iv) *Measurement of the induced voltage.*—Messrs. Felton and Guilleaume have described in British Patent No. 8243/22 a method of measuring the ratio of the induced to the inducing voltage, both in magnitude and phase. In Fig. 31, $W/2$, $W/2$ are fixed resistances, each of 25 000 ohms, m the fixed coil, and n the moving coil of a variometer, r a small variable resistance. In taking a test, r and n are adjusted until silence is obtained in the telephone T. Then the current in the branch circuit, $I_a = V_1/W$ approx.

Voltage across $r = rI_a$.

Voltage across coil n $= MI_a$, where M is the mutual inductance between the coils.

Total voltage $= (r + j\omega M)I_a$ and this is equal and opposite to the induced voltage V_2.

$$\therefore\ \frac{V_2}{V_1} = \frac{r + j\omega M}{W} \quad . \quad . \quad . \quad . \quad (83)$$

Since the balancing circuit does not carry any current the induced line behaves as if it were insulated. In practice, both the supply and the telephone must be connected through screened transformers to avoid capacity effects, and a reversing switch is provided on the listening pair to obtain the correct phase relationship.

It is to be noted that the ratio V_2/V_1 as measured in this way is not the same as occurs in practice, where the impedance of the listening instrument considerably alters the value; this is shown in equation (14z) *et seq.*

(v) *Measurement of interference with speech.*—The methods discussed so far all necessitate the use of a single-frequency current, and while it is true that such tests taken over a range of frequencies supply far more information about the line than does a single test with speech, in the present stage of development of the art the speech test is the ultimate criterion.

From a preceding Section we see that the interference coefficients are vector quantities which vary both in magnitude and direction with frequency. Consequently the induced current will alter in intensity and phase with frequency, and, inasmuch as this variation may be quite irregular, no measurement at a single periodicity can be taken as being representative of the behaviour over the whole range of frequencies in speech. This is different from the measurement of the transmitting qualities of a line, in which case the attenuation varies in a regular manner with frequency, and $\omega = 5\,000$ is taken as the mean speech frequency.

The principle of speech tests is to compare the volume of the induced current with the corresponding volume obtained through an adjustable network or "artificial cable," the input current and/or voltage being the same

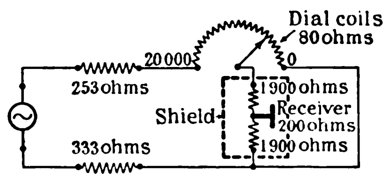


FIG. 32.—Cross-talk meter.

in both cases. By means of a switch a telephone is placed alternately in the listening circuit in the cable and on the output terminals of the network; the latter is varied until the intensity of sound is the same in both positions.

The "artificial line" can be used either in parallel or in series with the cable. In the first case the impressed voltages are equal, and in the second the currents entering are equal. When the meter has the same impedance as the cable, both conditions are fulfilled, but otherwise it is necessary, in giving results, to state the method of connection.

(vi) *The standard cable.*—The earliest method adopted was the use of the standard cable as the adjustable network, arising out of its employment for the measurement of attenuation. It is constructed of condensers and resistances, and is made to approximate to a line having the following constants per mile loop:— $R = 88$ ohms, $L = 1$ mH, $C = 0\cdot054\ \mu$F, $G = 1$ micromho, attenuation $= 0\cdot1065$. The equivalent length of the artificial cable is varied by means of switches, and the instrument is calibrated to read in miles of standard cable.

(vii) *The Western Electric cross-talk meter.*—This is probably the most widely used instrument in this country, and has been adopted by the British Post Office. It consists essentially of a form of universal shunt (Fig. 32) by which a known fraction of the total current passes through the telephone, and additional resistances are inserted so that the resistance of the combination is practically constant for all positions of the switch arm; the value is 666 ohms, using a 60-ohm Bell receiver of the ordinary type. The instrument is calibrated to express the current in the telephone as a fraction in millionths of the total current passing through the meter. If V_m = the voltage on the terminals of the meter, and I_m = the current passing through it, then $I_m = V_m/666$; if n is the reading then the current in the telephone,

$$I_t = \frac{nV_m}{666 \times 10^6} \quad . \quad . \quad . \quad . \quad . \quad (84)$$

The cross-talk meter can be used with a source of alternating current of adjustable frequency to obtain the variation of current in the telephone with frequency. Such a curve will correspond approximately to the variation of the modulus of the interference coefficient, but will be modified owing to the alteration in the impedance of the telephone receiver and transformers. Further, the source of alternating current must be a pure sine wave, as the presence of harmonics may give misleading results. (It is to be noticed that harmonics do not cause error in the null methods, but only make the balancing somewhat more difficult.)

Meter in parallel.

(*a*) *Cross-talk.*

AB/CD.

Equation (15*z*) gives

$$I_t = \frac{Z_1Z_2}{(Z_1 + 4r)(Z_2 + Z_t + 4r)} \cdot \frac{F}{4}V_1$$

Since the meter is in parallel, $V_m = V_1$.

$$\therefore\ n = \frac{666 \times 10^6 Z_1Z_2}{(Z_1 + 4r)(Z_2 + Z_t + 4r)} \cdot \frac{F}{4} \quad . \quad (85)$$

The equation for CD/AB is similar, Z_1 and Z_2 being interchanged.

(*b*) *Overhearing.*

(i) +/AB.

Equation (23*z*) gives

$$I_t = \frac{-Z_1Z_p}{(Z_p + r)(Z_1 + 4r + Z_t)} \cdot \frac{G}{2}V_1$$

$$\therefore\ n = \frac{666 \times 10^6 Z_1Z_p}{(Z_p + r)(Z_1 + 4r + Z_t)} \cdot \frac{G}{2} \quad . \quad . \quad (86)$$

(ii) AB/+.

Equation (25*z*) gives

$$I_t = \frac{-Z_1Z_p}{(Z_p + r + Z_t)(Z_1 + 4r)} \cdot \frac{G}{2}V_1$$

$$\therefore\ n = \frac{666 \times 10^6 Z_1Z_p}{(Z_p + r + Z_t)(Z_1 + 4r)} \cdot \frac{G}{2} \quad . \quad . \quad (87)$$

The corresponding equations for +/CD and CD/+ are obtained from equations (86) and (87) respectively, by writing Z_2 for Z_1 and H for G.

Meter in series.

(*a*) *Cross-talk*, AB/CD.—If I_1 is the input current into the cable, then $I_1 = V/Z_1$.

$$\therefore \text{ From (15}z\text{)},\quad I_t = \frac{Z_1^2Z_2}{(Z_1 + 4r)(Z_2 + Z_t + 4r)} \cdot \frac{F}{4}I_1$$

For the meter, $I_t = nI_m/10^6$ and, since the meter is in series with the cable, $I_m = I_1$.

$$\therefore n = \frac{10^6 Z_1^2 Z_2}{(Z_1 + 4r)(Z_2 + Z_t + 4r)} \cdot \frac{F}{4} \quad . \quad . \quad (88)$$

(*b*) *Overhearing*, +/AB.—In a similar way we find

$$n = \frac{10^6 Z_p^2 Z_1}{(Z_p + r)\ (Z_1 + 4r + Z_t)} \cdot \frac{G}{2} \quad . \quad . \quad (89)$$

$$\text{AB}/+,\ n = \frac{10^6 Z_1^2 Z_p}{(Z_p + r + Z_t)\ (Z_1 + 4r)} \cdot \frac{G}{2} \quad . \quad . \quad (90)$$

etc.

The equations for the cross-talk meter are given in enable proper comparison to be made between lines of different characteristics.

(viii) *Correction of cross-talk meter readings.*—Equation (31) gives as the true value of the interference in millionths, $n = \frac{1}{2}J\sqrt{(Z_1Z_2)} \times 10^6$, where $J = \frac{1}{4}F$ for cross-talk, and $-\frac{1}{2}G$ or $-\frac{1}{2}H$ for overhearing. Combining this with the equations in the previous Section, we can obtain the correction factor k by which it is necessary to divide the meter readings to allow for the effect of the external apparatus and for the difference in impedance between the disturbed and the disturbing circuits. The values for k are given in Table 2.

Using "4006A" repeating coils, r is 35 ohms, and for a 60-ohm Bell receiver Z_t is approximately 200 ohms. In Fig. 33, k is plotted against various values of the side-circuit impedance; for the overhearing two cases

TABLE 2.

	Side/side	Phantom/side	Side/phantom
Meter in parallel	$\dfrac{2 \times 666\sqrt{(Z_1Z_2)}}{(Z_1 + 4r)(Z_2 + 4r + Z_t)}$	$\dfrac{2 \times 666\sqrt{(Z_sZ_p)}}{(Z_p + r)(Z_s + 4r + Z_t)}$	$\dfrac{2 \times 666\sqrt{(Z_sZ_p)}}{(Z_s + 4r)(Z_p + r + Z_t)}$
Meter in series	$\dfrac{2Z_1\sqrt{(Z_1Z_2)}}{(Z_1 + 4r)(Z_2 + 4r + Z_t)}$	$\dfrac{2Z_p\sqrt{(Z_sZ_p)}}{(Z_p + r)(Z_s + 4r + Z_t)}$	$\dfrac{2Z_s\sqrt{(Z_sZ_p)}}{(Z_s + 4r)(Z_p + r + Z_t)}$

some detail, as it is the practice of the British Post Office to test with the meter both in parallel and in series. It is seen that the differences between results obtained for +/AB and AB/+, and for meter in parallel are given (i) $Z_p = 0{\cdot}5Z_s$ shown in full lines, and (ii) $Z_p = 0{\cdot}4Z_s$ shown in broken lines.

It will be seen that unless they are corrected, the readings may be very misleading, particularly for cables

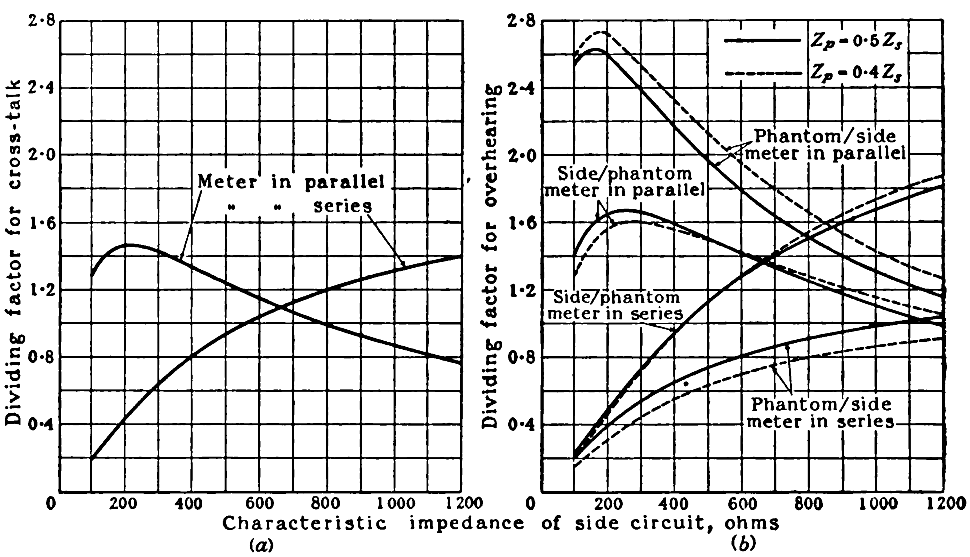


FIG. 33.—Correction factor for cross-talk meter readings.

and in series depend on the external apparatus. It is highly desirable that a standard of measurement be adopted which will be independent of the external apparatus and the method of connections, and depend on the cable only. This will simplify the testing and of small impedance, e.g. those with light loading. For $Z_s = 250$ ohms, the highest overhearing readings are given by the phantom/side connections with the meter in parallel; here $k = 2{\cdot}5$ when $Z_p = 0{\cdot}5Z_s$, so that a reading of 2 000 millionths really corresponds to a

value of 800 millionths. Particular caution therefore is necessary in comparing cross-talk meter figures with those obtained by different methods in a different system of units.*

(ix) *Difficulties of speech measurements.*—The measurement of interference with actual speech is one of the least satisfactory of the measurements in telephony. The ratio of the induced to the inducing current in the real cable varies irregularly, but generally increases as the frequency increases; on the other hand, the corresponding variation in the standard cable is in the reverse direction, the ratio decreasing with increasing frequency, whilst in the cross-talk meter the ratio is constant and independent of frequency. The real and the artificial cables behave differently towards the various harmonics in the speech current, and in consequence the observer has to attempt to equate by their sound in the telephone two currents of entirely different wave-form. In these circumstances the readings can vary widely with the conditions of test. It is difficult for the human ear to judge a complex sound by its intensity alone, without giving undue weight to some particular harmonic. The sensitivity of the ear varies for sounds of different pitch, it being most receptive to frequencies from 1 000 to 2 000 cycles per sec.; moreover, this variation is affected by the actual strength, for in louder sounds the lower tones have a certain "masking" effect. Thus the readings are affected by the strength of the current from the transmitter, by the presence of external noise, and by the position in which the receiver is held, whether tightly up to the ear or away from it. The results also vary considerably with the voice of the speaker, e.g. with the pitch, intensity and timbre, and again with the nature of the speech, e.g. the language, as determining the proportion of vowels and consonants. One possible solution is to arrange that the impedance/frequency curve of the artificial cable rises with increasing frequency.†

(x) *Relation between the interference with actual speech and at various frequencies.*—Let the angular frequencies of the components of the currents with actual speech be $\omega_1, \omega_2, \omega_3 \ldots$ and let the proportions of the total power at these frequencies be $k_1, k_2, k_3 \ldots$ etc., respectively; further let the values for the interference be Ψ_1 at ω_1, Ψ_2 at ω_2, etc.

The power in the disturbing circuit,

$$P_1 = k_1 P_1 + k_2 P_1 + \ldots$$

The power in the disturbed circuit

$$P_2 = k_1 \Psi_1 P_1 + k_2 \Psi_2 P_1 + \ldots$$

$$\therefore \Psi_{\text{speech}} = P_2/P_1 = k_1 \Psi_1 + k_2 \Psi_2 + \ldots \qquad (91)$$

Section 7.—Reduction of Interference.

The problem has been attacked in two ways, (*a*) by reduction all along the length of the cable, e.g. the method of cross-jointing as used in England and America, and the method of inserting small fixed condensers as used in Germany, and (*b*) by the use of apparatus at the ends only.

(i) *Cross-jointing.*—This method, as applied to the reduction of capacity unbalances in underground trunk cables (coil-loaded) was developed by the P.O. Research Department * in England and independently by the Western Electric Co.† in America.

From a consideration of Section 4 A (i), we can see that if the wires A and B are interchanged, the signs of $p - q$, $p + q$, and u are reversed, leaving $r + s$ and v unaltered; if C and D are interchanged, then the signs of $p - q$, $r + s$ and v are reversed, leaving $p + q$ and u unaltered; if A and B as well as C and D are interchanged, then all the characteristics change sign except $p - q$. Again, if the pairs are interchanged, the relevant overhearing characteristics are interchanged as well.

In the multiple-twin form of construction, one quad can be jointed to another in one of eight ways:—

(1) With the pairs straight:

(*a*) AB straight and CD straight.
(*b*) AB straight and CD crossed.
(*c*) AB crossed and CD straight.
(*d*) AB crossed and CD crossed.

(2) With the pairs crossed:

(*a*) AB straight and CD straight.
(*b*) AB straight and CD crossed.
(*c*) AB crossed and CD straight.
(*d*) AB crossed and CD crossed.

When a number of lengths are joined together, the resultant capacities are the algebraic sums of the corresponding capacities in the separate sections, provided the total length is short, and the joints can generally be designed by suitable crosses to reduce all the characteristics. The length of cable between loading coils in trunk mains ($1\frac{1}{3}$ to $2\frac{1}{2}$ miles) fulfils this condition very nearly, as the wave-length of the unloaded cable is considerable, and therefore balancing on the plain summation principle is permissible. Each section of cable between loading points is treated as a separate unit, and in English practice the characteristics are balanced out so that the following values are not exceeded:—

$$\begin{array}{rl} p - q & 80\ \mu\mu\text{F} \\ \left.\begin{array}{r} 2(p+q)+u \\ 2(r+s)+v \end{array}\right\} & 110\ \mu\mu\text{F} \\ \left.\begin{array}{r} u \\ v \end{array}\right\} & 200\ \mu\mu\text{F} \end{array}$$

This method can be applied to continuously loaded cables, but on account of the higher distributed inductance the wave-length is less than for an unloaded cable and the sections have to be considerably shorter. The inductance and resistance unbalances have to be reduced at the same time and this complicates the balancing. If capacity and inductance are balanced out

* See also H. de Voogt: "The Measurement of Cross-talk," *Electrician*, 1925, vol. 94, p. 332.

† F. Breisig: "Über das Nebensprechen in Fernsprechkreisen," *E.T.Z.*, 1921, vol. 42, p. 933.

* S. A. Pollock: *Journal of the Institution of Post Office Electrical Engineers* (April 1914 and January 1915), also Technical Instruction 19, P.O. Engineering Department.

† British Patent Nos. 2009 and 2508 of 1913.

separately in different stages, it is necessary to work in yet shorter lengths. This is undesirable as adding to the number of joints and multiplying the testing and clerical work.

The author has extended the crossing method to apply to the general case where the unbalances are complex quantities and the propagation effect has to be taken into account; it has been developed to deal more particularly with continuously loaded cables.

(ii) *Procedure in the author's method.**—The results of crossing are similar to those in the simpler case, viz. interchanging the wires of a pair reverses the sign of its relevant overhearing coefficient; the sign of the cross-talk coefficient is altered if one pair is crossed and is the same if both are crossed; the magnitudes are unaffected. The corresponding terms in the summation formulæ are altered in the same way.

Briefly, the interference coefficients of each section of cable are measured by means of the bridge described in Section 6 (iii). In order that the behaviour of every part shall be the same as when it forms a portion of the completed line, all measurements are taken with the distant end terminated. The sections are grouped together, and the effective coefficients of each quad are calculated by means of equations (62) and (63) to obtain the value when measured from the end of its group. The joints between sections are arranged by suitable crosses so that the total value of each interference coefficient is reduced below some predetermined value. The groups are tested to check the calculated figures, and the process is repeated in connecting up the groups.

It is evident from the equations that a balance for one particular frequency does not hold good for all others, in fact, under certain conditions, the arrangement that will be the best for one frequency is the worst for another. It is impossible to cancel an unbalance by any other unbalance situated at a distance from it, so that the resultant is zero for all frequencies; but the smaller the distance separating the two, the wider the range of frequencies over which the cancellation is effective. The first principle in selection therefore is that every large unbalance must be neutralized by an unbalance of the same order of magnitude, located as close to it as possible. If the cable contains a large number of quads, and if the quads can be crossed indiscriminately in the joints, then this condition can generally be met. The difficulties arise when the number of cores is limited, and especially when the manner of jointing is restricted. In submarine cables it is desirable to avoid mechanical discontinuities, and the size of the joint must be the same as the rest of the cable; consequently crossing over of quads is not practicable, and when the joint in one quad of a layer is determined the remaining quads have to follow in their normal positions. This severely limits the possibility of reducing the characteristics to small values. On the other hand, if the order of the sections is not fixed, they can be arranged so as to help to reduce the unbalances, and in the case of a submarine cable where the joints are made in the factory this is of considerable assistance.

* British Patent No. 241972.

The second principle is to arrange that the band of frequencies over which the coefficients are reduced, covers the region of the most important harmonics in speech. Generally the interference/frequency curve rises more or less regularly with frequency. The effect of balancing at one definite frequency is to cause a

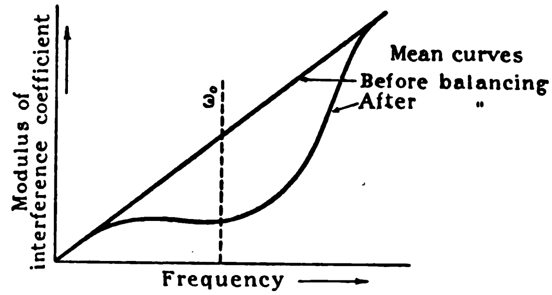


FIG. 34.—Effect of balancing at a single frequency, ω_0.

depression in the curve over a region of which that frequency is the centre. The result is shown in Fig. 34; the curve is first approximately level and then rises steeply. In transmission tests it is found that $\omega = 5\,000$ represents the mean speech frequency, and we may take the region $\omega = 3\,000$ to $\omega = 10\,000$ as containing the most important frequencies. The author has found that balacing at $\omega = 7\,000$ gives good results on total

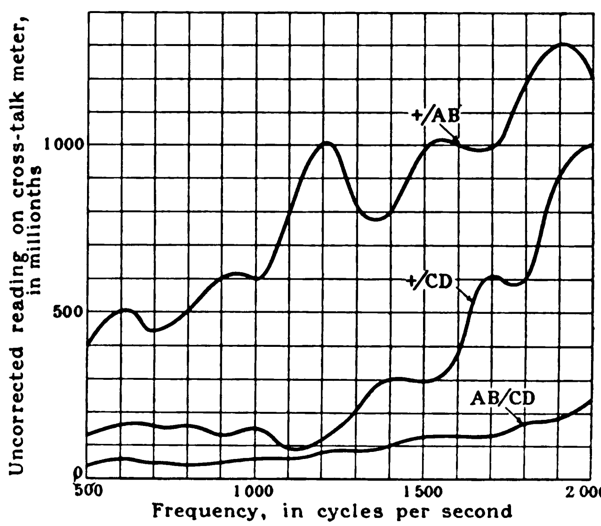


FIG. 35.—Variation of interference with frequency on a continuously loaded cable. $Z_s = 480$ ohms; $Z_p = 190$ ohms.

lengths up to $\alpha l = 1 \cdot 0$. Fig. 35 shows some typical curves, the cross-talk meter readings, which are approximately proportional to the modulus of the interference coefficient, being plotted against frequency.

In the joining up of groups to form longer lengths a difficulty arises if the same frequency be used. Where the resultant has been reduced to a low value at $\omega = 7\,000$, it no longer bears any relation to the rest of the interference/frequency curve, and balancing on these figures may give worse results. The procedure then is to use a different frequency for each stage of

the balancing, e.g. $\omega = 7\,000$ for forming the initial groups, and $\omega = 5\,000$ for joining these, or if three stages are required, then $\omega = 10\,000$, $7\,000$ and $5\,000$ respectively would be suitable.

A point to be noticed is that the interference has to be reduced at both ends, and for a short cable this means that every section has to be tested from both ends and the groups balanced from both ends; on a long cable it would suffice to balance each half from one end only, and join up so that these are the ends in the total length.

In applying equations (62) and (63), the labour is much reduced by constructing charts so that the effective values of the interference coefficients can be read off. For this purpose, the author works from the bridge readings as they stand rather than from the actual interference coefficients. The equations for this case can be written :—

$$g' = (g \cos 2al + \omega c \sin 2al) e^{-2\beta l} \quad . \quad . \quad (92)$$

$$c' = (c \cos 2al - (g/\omega) \sin 2al) e^{-2\beta l} \quad . \quad . \quad (93)$$

If the bridge figures are r ohms and c $\mu\mu$F, then

$$\frac{r'}{10^8} = \left(\frac{r}{10^8} \cos 2al + \frac{\omega c}{10^{12}} \sin 2al\right) e^{-2\beta l} \quad . \quad . \quad (94)$$

$$\frac{c'}{10^{12}} = \left(\frac{c}{10^{12}} \cos 2al - \frac{r}{\omega \times 10^8} \sin 2al\right) e^{-2\beta l}. \quad (95)$$

For $\omega = 7\,000$, these become :—

$$r' = (r \cos 2al + 0{\cdot}7c \sin 2al) e^{-2\beta l} \quad . \quad . \quad (96)$$

$$c' = \left(c \cos 2al - \frac{r}{0{\cdot}7} \sin 2al\right) e^{-2\beta l} \quad . \quad . \quad (97)$$

For a given length $\cos 2al$, $\sin 2al$, $e^{-2\beta l}$ are constants, and the equations are of the form :—

$$r' = Ar + Bc \quad . \quad . \quad . \quad . \quad . \quad . \quad (98)$$

$$c' = Ac - Cr \quad . \quad . \quad . \quad . \quad . \quad . \quad (99)$$

where A, B and C are constants. The corresponding graphs are straight lines and enable the effective values to be read off quite simply. Examples are shown in Figs. 36 and 37. A chart has to be constructed corresponding to each distance, i.e. if five sections are joined to form a group, four charts are required for the cross-talk and four for the overhearing.

An example will help to make the foregoing clearer. The group to be joined up consists of five sections, and we shall consider one quad in each section. The test-results on the sections at $\omega = 7\,000$ are shown in Table 3.

From the known constants of the cable, the following values are calculated :—

Cross-talk, βl per section length $= 0{\cdot}0097$
al per section length $= 0{\cdot}1528$

Overhearing, βl per section length $= 0{\cdot}0114$
al per section length $= 0{\cdot}1786$

TABLE 3.

Section	F		G		H	
	c	r	c	r	c	r
	μμF	ohms	μμF	ohms	μμF	ohms
1	− 100	− 40	+ 530	+ 220	− 1 590	− 220
2	+ 275	+ 35	+ 1 570	+ 260	+ 160	− 90
3	− 415	− 70	+ 200	+ 150	+ 210	− 90
4	− 480	− 45	+ 120	− 40	+ 620	+ 190
5	+ 445	+ 80	+ 110	+ 100	+ 80	+ 90

Length of sections $= \frac{1}{2}$ mile.

The equations for obtaining the effective interference coefficients are :—

(a) *Cross-talk.*

(1) Distance $= \frac{1}{2}$ mile (one section length)
$c' = 0{\cdot}930c - 0{\cdot}422r$; $r' = 0{\cdot}930r + 0{\cdot}207c$

(2) Distance $= 1$ mile (two section lengths)
$c' = 0{\cdot}779\,c - 0{\cdot}737r$; $r' = 0{\cdot}779r + 0{\cdot}386c$

(3) Distance $= 1\frac{1}{2}$ miles (three section lengths)
$c' = 0{\cdot}562r - 1{\cdot}062r$; $r' = 0{\cdot}562r + 0{\cdot}520c$

(4) Distance $= 2$ miles (four section lengths)
$c' = 0{\cdot}303c - 1{\cdot}225r$; $r' = 0{\cdot}303r + 0{\cdot}600c$

(b) *Overhearing.*

(1) Distance $= \frac{1}{2}$ mile (one section length)
$c' = 0{\cdot}921c - 0{\cdot}456r$; $r' = 0{\cdot}921r + 0{\cdot}224c$

(2) Distance $= 1$ mile (two section lengths)
$c' = 0{\cdot}746c - 0{\cdot}841r$; $r' = 0{\cdot}746r + 0{\cdot}412c$

(3) Distance $= 1\frac{1}{2}$ miles (three section lengths)
$c' = 0{\cdot}500c - 1{\cdot}117r$; $r' = 0{\cdot}500r + 0{\cdot}547c$

(4) Distance $= 2$ miles (four section lengths)
$c' = 0{\cdot}210c - 1{\cdot}255r$; $r' = 0{\cdot}210r + 0{\cdot}615c$

The charts corresponding to "cross-talk, distance $= \frac{1}{2}$ mile," and "overhearing, distance $= 2$ miles" are

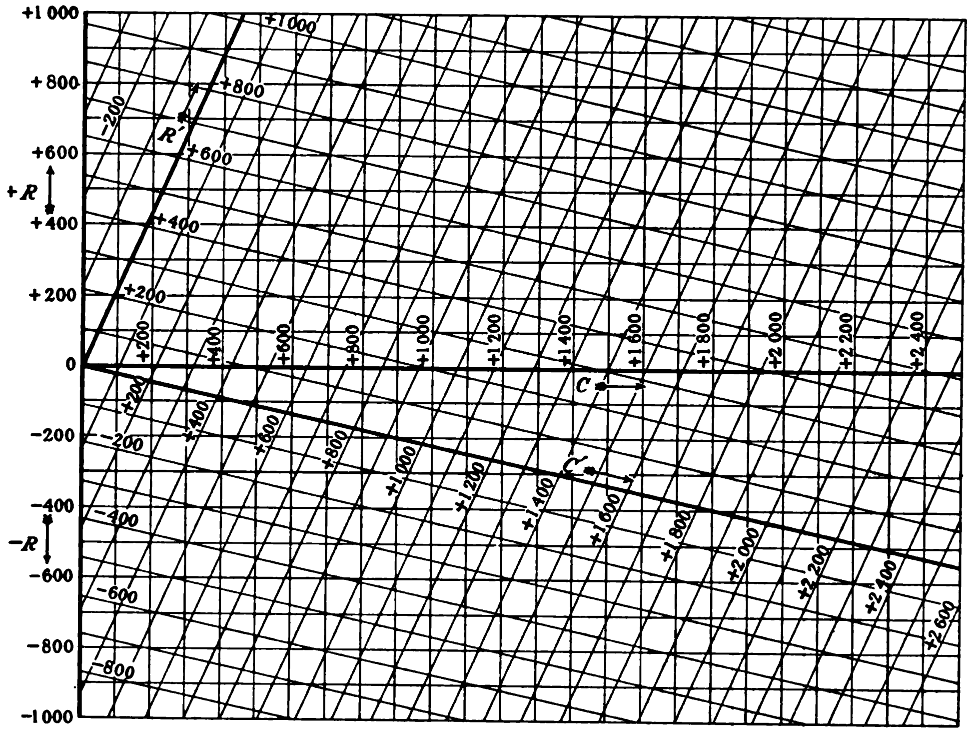


FIG. 36.—Cross-talk. Distance = ½ mile.

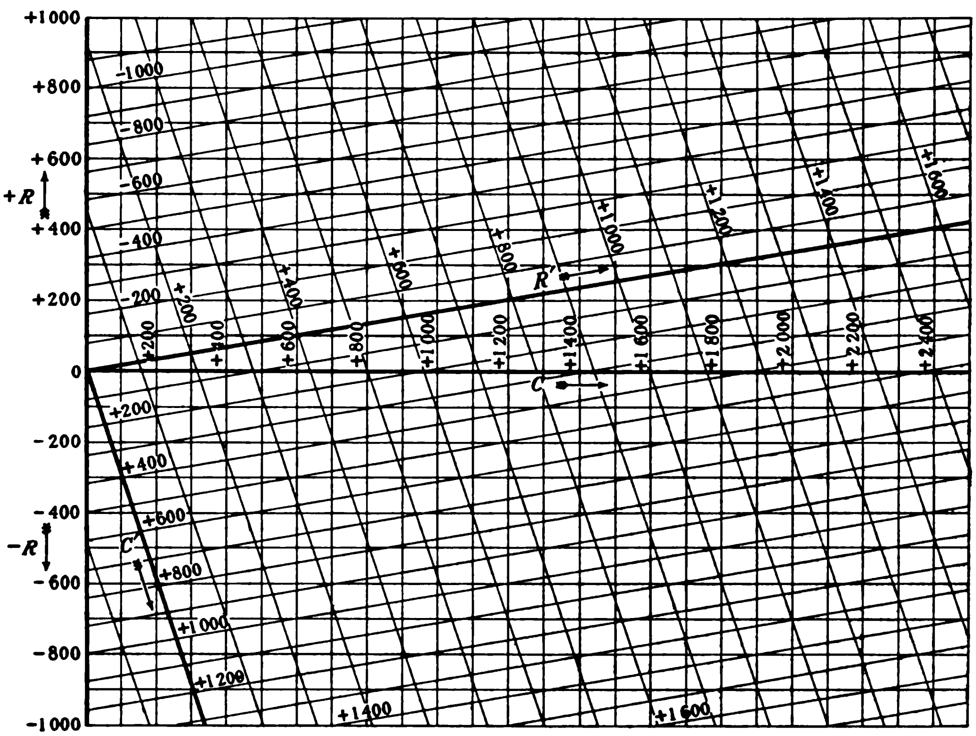


FIG. 37.—Overhearing. Distance = 2 miles.

those given in Figs. 36 and 37. The order of joining up the sections and the crosses in the cores is shown in Table 4, together with the effective values and the resultant totals.

(iii) *Balancing before laying-up*.—The efficacy of the crossing method depends upon the freedom of choice in selecting the quads which are to go together. Before the quads are laid up this choice is much wider, and balancing can be carried out up to the longest length which can be handled by the stranding machine. No difficulty is experienced as regards inductance and resistance unbalances (in a continuously loaded cable). In the case of a cable with paper dielectric, the lead sheath is not put on until after the quads are laid up. Consequently the capacity unbalances cannot be measured in the usual way on the quads before stranding, and, moreover, owing to the damp condition of the paper, ordinary capacity measurements are not possible. The author has found that by using a bridge in which the leakance as well as the capacity are balanced, as described in Section 6 (iii), results are obtained which are comparable with the capacity unbalances after laying up and casing in lead; the extent of agreement depends on the dampness of the dielectric and the amount of crushing the quad receives in the stranding and lead-sheathing processes. The figures, particularly those for the cross-talk, are sufficiently reliable to be used for a preliminary balance, and the method has proved of considerable value.*

(iv) *Balancing by condensers*.—This method has been developed by the firm of Siemens and Halske † in Germany and has been largely used on the coil-loaded cables in that country. In each quad three fixed condensers are connected between the cores so as to equalize the partial capacities, each loading-coil section being treated as a unit. Referring to Section 4A (i), let $p - q = f$, $p + q + \frac{1}{2}u = g$, and $r + s + \frac{1}{2}v = h$. If equal capacities be added between BC and AD, the cross-talk will be altered without affecting the overhearing; if added equally to BC and BD, only g is altered, and if to BD and AD, only h is altered. The required values to be added are the totals as shown in Table 5. It is understood that where the totals are negative, the condensers are inserted in the opposite arms.

The condensers are made up with paper insulation and are sealed into glass tubes; they are placed either in a separate pot or in an enlarged lead sleeve over the joint. Out-of-balance resistance is compensated by inserting small portions of high-resistance wire.

The author is not aware if the condenser method has been used on continuously loaded cables. On account of the shorter wave-length of the loaded core it would require that the condensers be inserted at more frequent intervals if the same degree of compensation is required. As explained in Section 4, on a loaded cable, provided it is suitably terminated, shunt capacity will compensate approximately the self and mutual unbalances as well as the capacity unbalances. The required values for the balancing condensers can be ascertained by measuring each section, not with the distant end free in the usual way, but terminated by a network equivalent to the infinite line.

(v) *Balancing at the ends of the line*.—Both the crossing and the condenser methods involve a considerable amount of work, especially on a long cable, and if the unbalances could be compensated easily by apparatus at the ends only, it would simplify and cheapen the manufacture and laying.

At any particular frequency the unbalance consists of a capacity and leakance. The capacity can be easily compensated, but the leakance is more difficult,

TABLE 4.

Section	Cores	F		G		H		F′		G′		H′	
		c	r	c	r	c	r	c'	r'	c'	r'	c'	r'
		μμF	ohms	μμF	ohms	μμF	ohms	μμF	ohms	μμF	ohms	μμF	ohms
4	AB CD	−480	−45	+120	− 40	+ 620	+190	−480	− 45	+120	− 40	+ 620	+190
2	DC BA	+275	+35	−160	+ 90	−1 570	−260	+230	+ 90	−190	+ 50	−1 320	−590
1	AB DC	+100	+40	+530	+220	+1 590	+220	+ 50	+ 70	+210	+380	+1 000	+820
3	CD BA	+415	+70	+210	− 90	− 200	−150	+150	+250	+200	+ 70	+ 70	−180
5	BA CD	−445	−80	−110	−100	+ 80	+ 90	− 30	−290	+100	− 80	− 100	+ 60
					Totals			− 80	+ 75	+440	+380	+ 270	+300

TABLE 5.

Position	AC	BC	BD	AD
Cross-talk ..	—	$\frac{1}{2}f$	—	$\frac{1}{2}f$
Overhearing on AB	—	$\frac{1}{2}g$	$\frac{1}{2}g$	—
Overhearing on CD	—	—	$\frac{1}{2}h$	$\frac{1}{2}h$
Totals	—	$\frac{1}{2}(f + g)$	$\frac{1}{2}(g + h)$	$\frac{1}{2}(f + h)$

* British Patent Specification No. 239957.
† British Patent Specification No. 147013.

as it is of the order of hundreds of megohms. The main obstacle, however, is that the unbalance varies irregularly with frequency, and thus it is necessary to design a network in which both the capacity and the leakance components vary in some predetermined, irregular way. Networks composed of a series of resonant circuits, each corresponding to a hump in the frequency curve,* have met with partial success, but the reduction in interference is not nearly so complete as can be obtained by balancing along the length of the line. Another objection is that such networks cannot be designed to introduce only just the required out-of-balance impedance; their impedance is commensurate with that of the line, and when placed in shunt across it they lower the transmission efficiency. The same applies to balancing networks in series with the line, with the additional objection that these cannot compensate cross-talk, but only overhearing.

The author desires to express his thanks to the management of Messrs. Siemens Bros. & Co., Ltd., Woolwich, for permission to present this paper.

APPENDIX I.

Star-mesh Conversion.†

In any network, a star of n rays $OA = a$, $OB = b$, $OC = c \ldots ON = n$ (Fig. 38), may be replaced by a

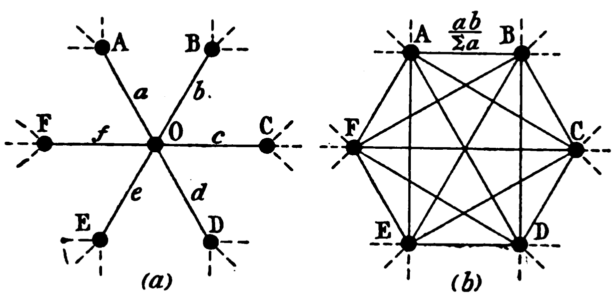


Fig. 38.—Star-mesh transformation.

mesh of $\frac{1}{2}n(n-1)$ conductors joining every pair of the points A, B, C . . . N (O being eliminated) without affecting the rest of the network; then for conductance operators,

$$AB = \frac{ab}{\Sigma a}, \quad BC = \frac{bc}{\Sigma a}, \text{ etc.} \quad . \quad . \quad (100)$$

where $\Sigma a = a + b + c + \ldots n$.

For impedance operators,

$$AB = ab\Sigma\left(\frac{1}{a}\right), \quad BC = bc\Sigma\left(\frac{1}{a}\right), \text{ etc.} \quad . \quad (101)$$

where $$\Sigma\left(\frac{1}{a}\right) = \frac{1}{a} + \frac{1}{b} + \frac{1}{c} + \ldots \frac{1}{n}$$

* H. T. Wernen: discussion on I. G. Hill's paper "Phantom Telephone Circuits," *Journal I.E.E.*, 1922, vol 60, p. 702.

† A. Rosen: "A New Network Theorem," *Journal I.E.E.*, 1924, vol. 62, p. 916. G. A. Campbell: "Direct Capacity Measurement" *Bell System Technical Journal*, July 1922.

APPENDIX II.

Transformation of Mutual Impedance.

In Fig. 39 (a) the arms OA, OB are of self-impedance Z_a, Z_b, and there is a mutual impedance m between them. They can be transformed into a star free from mutual impedance * [Fig. 39 (b)] in which the arms are $OC = -m$, $AC = Z_a + m$, $BC = Z_b + m$. This star can again be transformed into a mesh [Fig. 39 (c)] using equation (101).

Then

$$OA = Z_a[1 - (m/Z_b)]$$
$$OB = Z_b[1 - (m/Z_a)]$$
$$AB = Z_a + Z_b + 2m - (Z_a + m)(Z_b + m)/m$$

In terms of admittances, if the arms in Fig. 38 (a) are Y_a and Y_b, then

$$OA = \frac{Y_a}{1 - mY_b}$$
$$OB = \frac{Y_b}{1 - mY_a}$$
$$AB = \frac{mY_aY_b}{m^2Y_aY_b - 1}$$

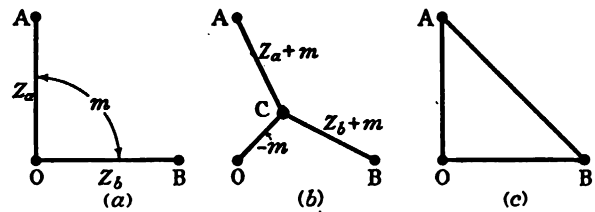


Fig. 39.—Transformation of mutual impedance.

If mY_a, mY_b are small so that their squares can be neglected compared with unity, then

$$\left.\begin{aligned} OA &= Y_a(1 + mY_b) \\ OB &= Y_b(1 + mY_a) \\ AB &= -mY_aY_b \end{aligned}\right\} \quad . \quad . \quad . \quad (102)$$

APPENDIX III.

Comparison between the Summation and Single Frequency Methods of Balancing.

In the simple summation method (A) the joints are so designed as to reduce the algebraic sums of the unbalances due to capacity, inductance and resistance respectively below predetermined limits, which are chosen so that the resulting interference with speech is within a certain value; similarly in the single-frequency method (B) the calculated residual has to be brought down below a definite value. In both cases, the residual R and the interference with speech are related by an equation of the form

$$\Psi_{\text{speech}} = K_1R^2 + K_2 \quad . \quad . \quad . \quad (103)$$

* G. A. Campbell: "Cisoidal Oscillations," *Transactions of the American I.E.E.*, 1911, vol. 30, p. 873. S. Butterworth: *Proceedings of the Physical Society of London*, 1921, vol. 33, p. 314.

and the method is valid only up to the point beyond which the term K_2 becomes excessively great. We shall investigate this relation for a simple case and show that, other things being equal, K_2 depends on the length of the sections in which the balancing is carried out, and it will appear that as the length is increased method (A) breaks down while method (B) can still be successfully applied. It is legitimate to assume that these deductions apply in the general case.

Consider the cross-talk between two similar long circuits of impedance Z_0. Equation (26) gives

$$\Psi = \frac{J^2}{4}Z_0^2 = \frac{F^2}{64}Z_0^2$$

From equation (91),

$$\Psi_{\text{speech}} = \Psi_1 k_1 + \Psi_2 k_2 + \ldots$$
$$= \frac{Z_0^2}{64}(F_1^2 k_1 + F_2^2 k_2 + \ldots) \quad . \quad (104)$$

assuming, as is the case approximately for loaded cables that Z_0 is independent of frequency.

Let there be a capacity unbalance $-B$ at the near end and another A at a short distance l. Then the residual by simple summation is $A - B = R_a$. The actual residual is

$$Ae^{-2\gamma l} - B = A(1 - 2\gamma l) - B \text{ approximately, since } \gamma l \text{ is small}$$
$$= A - B - 2jalA \text{ approximately}$$
$$= A - B - j\lambda\omega, \text{ where } \lambda = 2\sqrt{(LC)}lA.$$
$$\therefore \quad F = j\omega(A - B - j\lambda\omega)$$

and
$$F^2 = \omega^2\{(A - B)^2 + \lambda^2\omega^2\} \text{ in magnitude} \quad (105)$$
$$= \omega^2(R_a^2 + \lambda^2\omega^2) \quad . \quad . \quad . \quad . \quad . \quad (106)$$

$$\therefore \quad \Psi_{\text{speech}} = \frac{Z_0^2}{64}\{R_a^2\Sigma(\omega^2 k) + \lambda^2\Sigma(\omega^4 k)\} \quad . \quad . \quad . \quad (107)$$

In method (B), using a frequency ω_0, the residual is

$$A - B - j\lambda\omega_0 = R_b$$
$$\therefore \quad R_b^2 = (A - B)^2 + \lambda^2\omega_0^2$$

Substituting in (105), we have

$$F^2 = \omega^2\{R_b^2 - \lambda^2(\omega_0^2 - \omega^2)\}$$

$$\therefore \quad \Psi_{\text{speech}} = \frac{Z_0^2}{64}\{R_b^2\Sigma(\omega^2 k) + \lambda^2\Sigma(\omega^4 k) - \lambda^2\omega_0^2\Sigma(\omega^2 k)\} \quad (108)$$

Example.—Let the speech current contain only the three frequencies $\omega = 3\,000$, $5\,000$ and $7\,000$ radians per sec., and assume the corresponding proportions of the total energy to be $k_{3\,000} = \frac{1}{4}$, $k_{5\,000} = \frac{1}{2}$, $k_{7\,000} = \frac{1}{4}$.

Let $A = 1\,000\mu\mu\text{F}$, $b = -800\mu\mu\text{F}$, $Z_0 = 500$ ohms, $a = \omega/20\,000$, $l = 1$ mile.

Then
$$\lambda = 10^{-13}$$
$$\Psi_{3\,000} = 0{\cdot}46 \times 10^{-8}$$
$$\Psi_{5\,000} = 2{\cdot}83 \times 10^{-8}$$
$$\Psi_{7\,000} = 10{\cdot}13 \times 10^{-8}$$

The proportions contributed by the three frequencies to the interference with speech are :—

$$\omega = 3\,000, \ \tfrac{1}{4}(0{\cdot}46 \times 10^{-8}) = 0{\cdot}115 \times 10^{-8}$$
$$\omega = 5\,000, \ \tfrac{1}{2}(2{\cdot}83 \times 10^{-8}) = 1{\cdot}415 \times 10^{-8}$$
$$\omega = 7\,000, \ \tfrac{1}{4}(10{\cdot}13 \times 10^{-8}) = 2{\cdot}532 \times 10^{-8}$$
$$\Psi_{\text{speech}} = \text{total} = 4{\cdot}062 \times 10^{-8}$$

Of this total, the amount independent of the calculated residual in the summation method is $3{\cdot}58 \times 10^{-8}$, and in the single-frequency method is $1{\cdot}49 \times 10^{-8}$. Thus in this case the uncontrolled factor in method (A) is disproportionately great, and therefore the residual is valueless as an indication of the result with speech; whereas in method (B) the uncontrolled factor is still small and the residual is a guide to the actual figure.

It will be observed that there is a greater proportion of the higher frequencies in the induced current than in the original, and a similar effect is obtained with inductance unbalances. It is for this reason that the frequency in method (B) is chosen to be higher than the mean speech frequency.

We may infer that, in general, the limiting factor K_2 in equation (103) will have the same form as the terms independent of the calculated residual in the simple case considered. For any given speech current those involving ω and k are fixed, and the criterion for comparing different cables is, for cross-talk,

$$K_2 \propto Z_0^2 LCl^2\overline{A}^2 \quad . \quad . \quad . \quad . \quad (109)$$

where l is the length of the sections and $\overline{A}$ is the average magnitude of the capacity unbalances.

Let
$$n_c = \frac{\text{unbalanced capacity}}{\text{actual capacity}} = \frac{\overline{A}}{LC}$$

Then
$$K_2 \propto C^2L^2l^4n_c^2 \quad . \quad . \quad . \quad . \quad (110)$$

Similarly for overhearing, which is due principally to self-inductance and capacity unbalances, we obtain

$$K_2 \propto C^2L^2l^4(n_c + n_l)^2 \quad . \quad . \quad . \quad (111)$$

where
$$n_l = \frac{\text{unbalanced inductance}}{\text{actual inductance}}$$

In equations (110) and (111), n_c and n_l represent the quality of the manufacture of the single sections.

DISCUSSION ON

"POWER FACTOR AND TARIFF."*

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, MANCHESTER AND BIRMINGHAM.

Mr. E. V. Clark (*in reply*) : I regret that none of those who took part in the discussion on the papers by Mr. Dorey and myself have entered the lists, either in support or in opposition, with regard to my contention that, under a rational tariff, and *ceteris paribus*, of two supply undertakings having equal energy load, the one with the lower power factor should show the better financial returns. This is a point where I seem fundamentally at variance with most of my critics, who appear to imply that power-factor correction by consumers is a natural aim of the undertaking. Mr. Woodhouse, for example, with a two-part tariff speaks quite cheerfully of consumers saving £2 000 and even £6 000 a year by installing apparatus for improving the power factor; whilst Mr. Bennett, with a similar tariff, considers that before long his staff will "convince" all his consumers that correction to about 0·9 power factor is a paying proposition for them. This seems a telling argument against the adequacy of the two-part tariff. Surely his staff are much better employed in convincing non-users of electricity how they may, to their own advantage, augment the gross revenue of the undertaking, than in convincing satisfied users how they may decrease it. While I fully agree with Mr. Kapp that we must have a salesman's tariff and eliminate all accountant's refinements that are found unnecessary, yet I consider it essential that the tariff should accord with the requirements of the accountant to such an extent that each consumer may install whatever apparatus he considers most desirable, without any attempt on the part of the undertaking's engineers to bias for their own ends his judgment as to how his requirements may best be met. If the consumer is to seek advice from the engineers of the supply undertaking, he should know that their only bias will be the inherent one of wanting to sell electricity. Two instances in a contractor's experience will illustrate my point. A client wanted a motor. One of 30 h.p. would have sufficed, but finding that a 50 h.p. motor was not much more expensive, and about as efficient at 30 h.p. load, he installed the larger size in order to have some reserve power. When next the contractor saw him, the client stated that an engineer of the supply undertaking had told him that he had been badly advised, that a 30 h.p. motor would have been a better proposition and that it was wasteful to put in the larger size. Naturally, the contractor was annoyed. In the other case, a small shop was run by a gas engine, fully loaded. A new machine, taking 3 h.p., was bought and electric drive decided on. Prices and efficiencies at 3 h.p. load being obtained for motors of various sizes, a 15 h.p. motor was chosen, in order that on occasions when overtime was required a few machines might be run without using the gas engine. "On applying to the undertaking for a service for a 15 h.p. motor," said the contractor, "I thought it discreet not to mention that the normal load would be only 3 h.p." Now it is quite unnecessary to say that in each case the supply was alternating current. It is unthinkable that a supply engineer should criticize the installation of a 50 h.p. d.c. motor for a 30 h.p. job, particularly in the Australian climate; whilst to persuade a client to install a 15 h.p. d.c. motor for a 3 h.p. load, and thereby take a definite step towards the ultimate supersession of a gas engine, is a thing about which the contractor would boast. In each case, the decision to adopt an electric motor was, as far as the consumer was concerned, entirely independent of the nature of the supply available. The only factors with which he was concerned were the costs of installation and of operation, and the value of convenience, reliability and reserve power. It is solely because the a.c. tariff in force was defective from the accountant's standpoint, that a proceeding quite satisfactory to the undertaking with a d.c. supply should call for criticism on the a.c. mains.

I also regret that no one has ventured to criticize or supplement the figures of my very rough estimate of the running costs of wattless component. I know of no estimate of an authoritative nature of such cost, whether for general use or for a particular case.* It seems highly desirable that the magnitude of such cost should be known with some approximation to accuracy; and I trust that an engineer with access to the records of some undertaking where power factor is a serious matter will collect and publish what information he can on the subject. Various critics have said generally that they consider the importance of lagging current to have been over-rated; but, on the other hand, in the discussion on the late Dr. Kapp's paper on "Improvement of Power Factor" (*Journal I.E.E.*, 1923, vol. 61, p. 111) Mr. Woodhouse said that "A consumer should be prohibited from having a power factor of the order of 0·5 or 0·6"; and though apparently he would arrange the prohibition not by regulation but by tariff, it is evident that he, at least, finds low power factor of serious moment.

Several speakers consider that the two-part tariff meets all reasonable needs; but it fails in that, whilst consumers are encouraged to install correcting devices, they are given no inducement to use them to the best advantage of the undertaking. For example, where condensers and auto-transformer are installed, the wise consumer will, on a two-part tariff, cut them out when his load is less than 75 per cent of his peak, in order to save the transformer losses. Again, synchron-

* Paper by MR. E. V. CLARK (see page 625).

* The late Dr. Kapp (*Journal I.E.E.*, 1923, vol. 61, p. 107 quotes) figures supplied by the Clyde Valley Electric Power Co. estimating that, with an average power factor of 0·72, the increased I^2R losses in generators, transformers, and 11 000-volt mains due to lagging current are 4·85 per cent. Other losses due to lagging current are referred to, but no estimate is given of their magnitude or of the losses in l.t. distributors.

ous and synchronous-induction motors are slightly less efficient with leading power factor than with current in phase, and a shrewd consumer will not overexcite them except at peak load, and then only if he has straight induction motors as well. Only a very small charge and bonus for wattless component are necessary to ensure that the consumer shall gain by phase-advancing as much as the plant he has installed can readily manage. The synchronous motor at 0·95 leading power factor is not more than 1 per cent less efficient than at unity power factor, whilst its wattless component is about 30 per cent of its energy component; and thus a meter bias which rates wattless component at $\frac{1}{20}$th the cost of energy component suffices to make operation at this leading current a paying proposition, whatever the state of the consumer's load.

Turning now to points raised by individual speakers, Mr. Kapp stresses the effect of poor power factor on voltage regulation; but the footnote which he criticizes refers to two consumers who are specified in the text as being neighbours. The voltage regulation of the whole of the system, except beyond the point where the two consumers' mains diverge, is improved by precisely the same amount, no matter which of the two should install the condensers postulated, provided that they are in circuit for the same hours in each case. Diversity factor I take to be $\Sigma P/P_0$, where P is the consumer's peak load, and P_0 is the combined peak load. For simplicity, consider a feeder supplying 10 consumers, each with one motor taking 20 kW at 0·8 power factor at peak load. Then P, the consumer's peak load of energy component, is 20 kW, and Q, the peak load of wattless component, is 15 kVA; ΣP is 200, and ΣQ is 150. If the energy diversity factor is 2, then the peak load P_0 on the feeder is 100 kW. In the unlikely case of its being caused by five motors at full load, the other five being switched off, this peak will have a power factor of 0·8; Q_0, the wattless component on the feeder, will be 75 kVA, and the diversity factor of wattless component will be the same as that of energy. But if, as is probable, peak load on the feeder is due to almost all motors running, with an average of half load on each, then it will have a power factor of about 0·7, and Q_0 will be 100 kVA, so that the diversity factor of wattless component, $\Sigma Q/Q_0$, will be 150/100, or 1·5. In general, it seems that diversity factor of wattless component is bound to be lower than that of energy component in any case where most consumers have their maximum power factors at their peak loads.

Mr. Hart's remedy for poor power factor, namely, to install no motors larger than is necessary, is very hard to enforce; for consumers, like supply undertakings, have to look ahead and install to-day plant suitable for the probable needs of the next few years. Further, where the load a motor is to carry is uncertain, it is far wiser to spend a few pounds more in a motor of ample size, than to risk a possible interruption due to its failure.

Mr. Romero falls into what I believe to be a very general error, in thinking that an annual charge based on kVA of consumer's peak load implies that capital charges on an undertaking are considered to be proportional to kVA and not to kW. This is quite wrong, as kVA's are added vectorially, and not algebraically. Thus, ignoring diversity factor and line losses, if station peak is Q_0 kVA with a phase angle of θ, and a consumer has a peak of Q kVA with a phase angle of ϕ, then this consumer increases the station peak, not by Q kVA, but by $Q \cos (\phi-\theta)$ kVA. Or, to take a specific case, if the station power factor is 0·7, a consumer whose peak is 100 kVA at 0·7 power factor adds 100 kVA and 70 kW to the station peak; while a consumer whose peak is 100 kVA at unity power factor, adds 70 kVA and 100 kW to the station peak. Hence, as far as these two consumers are concerned, it is legitimate to assess annual charges upon consumers' kVA of peak load, if the annual charges on the undertaking depend half on kW and half on kVA. This matter is well worthy of closer study than space allows of here. In this lies the secret of the inconsistency of the kVA charge mentioned in the footnote on page 628. That kVA is not an ideal basis for assessing annual charges is quite certain. It tends to overcharge those whose power factors are appreciably lower than that of the system as a whole, and also those who take a leading current, while it tends to undercharge those whose power factors are somewhat better than that of the system. These conclusions are, however, only arrived at by ignoring diversity factor, and the complexities of the problem are vastly enhanced if one attempts to take this into account, particularly as diversity factor is apt to be much lower for wattless component than for energy component, as I have pointed out above. The concrete case of cost of electricity that Mr. Romero works out seems to me to show the marked superiority of the three-part tariff over the two-part tariff. The former asserts that, on the assumed conditions, two consumers each having a peak load of 100 kW, and each taking 200 000 units per annum, one at 0·5 and the other at 0·9 power factor, are appropriately charged £1 447 and £950 respectively; while the essential argument of the three-part tariff is that of these two, the 0·5 power factor consumer, having the larger bill, is the more profitable to the undertaking and may be freely allowed to continue with his poor power factor as long as he chooses. Under the two-part tariff of £5 plus 0·5d. with which this three-part tariff is strictly comparable, the respective charges upon these two consumers are £1 417 and £972, the difference being £52 less than on the tariff which I advocate. But in view of the remarks of Mr. Woodhouse and Mr. Bennett, it is evident that under a two-part tariff the 0·5 power-factor consumer would be regarded as an unsatisfactory client and a fit subject for persuasion as to the merits of condensers. However, in view of the deficiencies of the kVA charge, I quite agree with Mr. Romero that the above 0·5 power factor consumer would pay an undue annual charge for his supply; though the extent of the overcharge is utterly indeterminate, without some knowledge of the normal power factor of the system. It must, however, be remembered that the case is quite an abnormal one, as it is a peculiar installation which has a power factor as low as 0·5 at peak load. And I should say that an essential requirement of a satisfactory salesman's tariff is that whilst it is reasonably equitable with ordinary consumers, it shall tend to overcharge rather than under-

charge abnormal ones. Mr. Fennell, for example, urges the use of a special tariff for those whose conditions the general tariff does not fit: but this is far more difficult to arrange if the usual tariff charges him too little than if it charges him too much. In the former case the consumer feels he has a genuine grievance. In the latter case he is gratified by a special concession. In general, I think that it is quite safe to say that, despite its defects, the kVA basis for the annual charge departs much less from the accountant's ideal than the kW basis, excepting, first, for consumers taking leading current at peak load, and, secondly, on systems where the power factor is in the neighbourhood of unity.

I regret that the legend attached to the schedule was not explicit. Consumer B, with average power factor of 0·8, nevertheless has the same peak-load power factor, 0·87, as A.

Mr. Howarth expresses the objection many consumers have to any annual charge; and undoubtedly for small consumers, where load factor is low and diversity factor high, a flat rate per unit, requiring but a single meter, has much to recommend it. But it is with consumers such as these that power factor is apt to be excessively poor. For such, the biased meter, set to rate wattless component at about 30 per cent of the cost of energy, i.e. with the two parts set to run 50 per cent fast and slow, should be very suitable, the normal flat rate being reduced 20 or 25 per cent when the change is made to charge per virtual unit. With two consumers, one alongside the station and one 10 miles away, there is of course a difference, both in capital costs and in running costs, in supplying them. Any adjustment of tariff with distance is much more suitably made with a multipart tariff than with a unipart one. In the case in question, the more distant consumer might entail capital charges 50 per cent greater than the nearer, running costs for energy 10 per cent greater, and running costs for wattless component 100 per cent greater. Any adjustment thought desirable can readily be introduced with a three-part tariff. I see no difficulty in answering the question "What does the biased meter measure?" The reply that it measures the total consumption of energy current plus a small percentage of the magnetizing current is probably far more satisfactory to the consumer than any answer that can be devised to the question "What is this power factor that you are bothering me to improve?" And with three-part tariff and biased meter it is only the contractor's salesman who would be troubled with having to answer this latter question.

Mr. Fennell raises the matter of the hour of the consumer's peak load. This introduces the whole question of diversity factor, which is the great stumbling block in any attempt to devise a universal tariff. Except for the difference in diversity factor of energy component and wattless component to which reference was made, the problem is much the same in a.c. and d.c. systems, and consequently was not specifically dealt with in the paper. There is no question but that whatever the form of tariff adopted for general use, those consumers whose load is such as to help to fill up the hollows in the daily or annual load curve are entitled to special concessions. The objection to making such concessions too great or too general is the risk of converting hollows into peaks, and peaks into hollows. The justification of the frequent practice of giving small consumers the choice between a flat rate and a tariff embracing an annual charge rests on the reasonable assumptions that, in general, the small consumer entails negligible cost in transformers and mains restricted to his sole use; and that where load factor is low, diversity factor is high. In advocating a three-part tariff, I certainly do not wish it to be thought that I consider this should be rigidly adhered to by a supply undertaking, to the exclusion of all others. On the contrary, I regard it as suitable for the basic tariff upon which all consumers might elect to be charged if they wished; but a flat tariff—preferably not per B.O.T. unit, but per virtual unit measured by a meter with appropriate bias—based upon a load factor appreciably lower than that of the station, should be offered to small consumers; while, as Mr. Fennell advises, special arrangements should be made, where profitable business may be secured at rates appreciably less than under the normal tariff, with power users whose circumstances are abnormal.

I entirely agree with Mr. Howarth, Mr. Hoseason, and others, that the squirrel-cage induction motor is for the consumer the most reliable and simple piece of electrical apparatus yet invented. My object in advocating a three-part tariff, and in devising a meter which takes wattless current into account to any extent desired, is in order that the supply undertaking may preach the simplicity of the induction motor to those with whom reliability is of prime importance, and the economy of phase correction to those who find cost of power a vital matter, with the full conviction that whatever kind of apparatus is installed, the sale of the electricity it consumes will be a source of adequate profit.

I am much interested to hear from Mr. Hargrove of a case where not only is a sine meter used but, in addition, a direct charge is levied for wattless component at a flat rate per kVA-hour. As he is the only speaker who has given the slightest encouragement to a tariff of this nature, may I invite him to consider my suggestion that the sine meter may be incorporated in the watt-hour meter by giving this a bias in the manner indicated? Not only does this reduce the number of meters required, but it should also simplify the assessment of the penalty in the case of consumers with poor load factor, and overcome any difficulty consumers may find in understanding why units recorded on one meter are priced eight times as much as those recorded on the other. The curves which Mr. Hargrove gives show very clearly the encouragement a tariff of this type gives to improvement of power factor beyond 0·9. If a bonus is allowed for leading wattless component, the curves given for lagging power factor also indicate the charge for leading current, if one reads "Decreased cost per cent" instead of "Increased cost per cent" upon the axis of ordinates. I surmise that the system on which this tariff is used enjoys an average power factor of 0·8 or better; for the tariff as described is much more favourable to consumers with poor power factor than is the more usual two-part tariff. I do not follow the reference to my having taken 0·8 power factor as standard. On the

contrary, my estimate of the cost of wattless component was based on an average power factor of about 0·7, which I took as being reasonable for an undertaking selling alternating current only, and having a lighting load small in comparison with its power load.

I quite agree with Mr. Hall that, as engineers, we should extend our influence towards the improvement of power factor, but would add "where economically justified," since, as pointed out by the late Dr. Kapp, improvement of a system beyond a certain point is not warranted. But just as those who use energy current wastefully must pay for their extravagance in their electricity bills, so should those who use wattless component wastefully; and on ethical grounds there seems to be no reason why supply tariffs should not be such that a demand for wattless current, whether it be used wisely or extravagantly, should be a source of profit to the undertaking. Regarding the matter from a technical standpoint, it is palpably absurd in any one installation to attempt to improve power factor by regarding each motor as an independent culprit, without reference to the others. On the contrary, economy results from overcorrecting such motors as lend themselves to correction, and leaving others alone. Similarly in any large system, the greatest economy will result in general from overcorrecting those installations most suitable for this purpose, and leaving alone those where improvement is not so readily effected. And in view of this fact, which seems to me to be indisputable, it becomes necessary to levy an extra charge on those who do not correct, in order to be able to give to those who overcorrect a rebate greater than would be justified if their installations were considered alone. Naturally, as an aid to a more extensive use of electricity, a progressive undertaking will have a staff of "consumers' engineers," whose main duty is to advise prospective and existing consumers how they may more efficiently make use of electricity. But it must surely hamper such men greatly in seeing matters from the consumer's point of view if they know that elimination of energy waste will react to the benefit of the undertaking only indirectly, whereas elimination of wattless current reacts at once to its pecuniary advantage. In many cases, e.g. replacement of one large motor by several small ones, one may secure a saving in energy at the cost of a poorer power factor, or vice versa. My argument with respect to a consumer's power factor is precisely the same as with the overall efficiency of his installation. Any improvement in either should result in a direct monetary benefit to the consumer, by a reduction in his power bill, and consequently in a slight reduction in the profits of the undertaking. It no more follows from this that an undertaking should deliberately encourage wattless current, than that it should encourage waste of energy. However, I am quite ready to meet Mr. Hall to this extent, regarding the matter from an ethical point of view. A power user may be presumed to know something about mechanical losses; and if he is satisfied to use an inefficient arrangement of plant, the undertaking may not unreasonably consider that he has duly weighed its cost against the capital charges involved in a more efficient lay-out. But the ordinary power user knows little about wattless current, and hence when he uses this extravagantly there is perhaps some onus on the undertaking to point out to him how economy is possible. As regards complication of metering and computing accounts, there is no reason why the biased meter should exceed the ordinary meter in cost by more than a few shillings; and by its use, whether in conjunction with a maximum demand instrument or alone, we may secure, I think, the benefits of an improved form of tariff, with no increase in number, and negligible increase in cost, of the requisite measuring instruments.

DISCUSSION ON

"THE ENGINEER: HIS DUE AND HIS DUTY IN LIFE."*

DUNDEE SUB-CENTRE, AT DUNDEE, 11 FEBRUARY, 1926.

Mr. J. Conway : In the title of the paper the "due" is placed before the "duty," but the author confines his subject mainly to the latter and practically ignores the former. In regard to the finding of engineers, I was very much struck by the statement of the schoolmaster, Dr. Johnston, who had observed that the fact that a boy can repair a bicycle pump, etc., does not necessarily mean that he has engineering ability. I should never have thought that anyone who was not an engineer would have put that on record, and it shows very keen observation. A desire to seek continual employment for the hands in many cases indicates a low level of intelligence, and the boy who likes to "potter" is a doubtful quantity. It appears to me that the right type of boy would find himself, if the profession were given the status which it deserves. A properly trained engineer is of as good a mental calibre as, say, a doctor. He therefore deserves the same status, and one of the reasons why he does not get the same recognition is because he is poorly paid. The engineer will never attain to that status until the qualifications required to practise in the profession are as rigid as those for medicine. At present the return is far too poor for the training and ability demanded. This raises the question of giving advice to others with regard to entering the engineering profession. When a youth is choosing his future career I consider that the question of greater importance is not "What will he like," but "What will he be able to earn a reasonable living at." At first sight this looks far from idealistic, but there is reason in it. For if a boy chooses merely by what he thinks he will like, he may later on be disappointed to find himself in an ill-paid profession in which there is very keen competition even for the minor posts. Certainly he may start out with a liking for his work, and with high ideals, but these will surely fade as a result of poor salaries and lack of opportunity. It is common practice in the electrical world, particularly among the large manufacturing firms, to point to "the interest of the work" or "the experience to be gained" as a sort of makeweight to the lightness of the salary. But it is not everyone who can afford such luxuries, and certainly one cannot live on them. An employer of labour told me some weeks ago that he had now great difficulty in obtaining apprentice mechanical engineers, and that the quality of such as he did obtain was the poorest he had ever known. We all know that nowadays the fitter compares very unfavourably with the municipal dustman, and still more unfavourably with the policeman, both unskilled occupations. I think, therefore, that there is a moral to be drawn from that employer's statement. Make the profession worth while, and we can pick and choose the raw material which may be allowed to enter it. As things stand at present, while our case is not so bad as that of the mechanical engineering industry, yet it appears to me that we must just accept the best material that offers.

Mr. W. Frain : In this exceptionally thoughtful and illuminating statement as to a managing engineer's ideal conduct there seems to be one omission—that of training himself to do always "the first things first," the main feature in which is roughly the allocation of work to others before taking up one's individual task, so that there shall be no time lost in waiting for instructions. I am afraid that the idea of preventing merely unsuitable youths from proceeding with engineering training is impracticable, if only because no one would take the responsibility of deciding upon a compulsory retirement from a selected career. In Dundee, however, there are very successful arrangements for elimination and for guidance of boys of 14, and again of about 16 years of age. A Sub-Committee of the Juvenile Advisory Committee of the Ministry of Labour, with a membership of about 70, visits every school and there endeavours to gauge the boys' qualifications and desires and, if needful, to place them in employment. Another Sub-Committee, along with representatives of employers and of trades unions, visits regularly the continuation schools and advises the boys. Lads observed there to be making good are selected for being brought up to staff jobs. There are, in addition, After-care Sub-Committees, industrial and moral. I agree that engineers have not taken much part hitherto in public life. I am confident that a welcome awaits them. During the past few years in the Dundee City Council, out of, say, 50 men, 5 have been associated with engineering, and their opinions on cognate matters have been much valued, and their help has been greatly used.

[The author's reply to this discussion will be found on page 884.]

WESTERN CENTRE, AT CARDIFF, 1 MARCH, 1926.

Mr. C. T. Allan : The quality of the paper itself and the amount of discussion it has elicited will, I hope, make it the forerunner of others upon the same subject. The engineer's training necessitates longer hours and more exacting work and his average salary is less than in the other professions, and by discussing this subject as the author has done we are increasing the status of the engineer. Perhaps if we chose our assistants purely by Dr. Johnston's method we might not always

* Paper by Mr. T. Carter (see page 193).

obtain the right article. A very necessary requirement for the pupil is common sense. A man may have a mathematical brain, but this does not signify that he can handle men or a large business. The young man who has done comparatively poorly at college usually realizes his shortcomings, takes his work seriously, plods on and frequently in the end passes the more brilliant theorist. In other words "doggedness does it." Of all the methods of training the potential engineer, the college, sandwiched with the works, is in my opinion the quickest and best system. Of the older systems, it is difficult to decide whether it is better to send a young fellow straight from school to college and afterwards to a works, or to a works first and college afterwards. The former method makes it easier for a youth to pass the examination, unless in the latter case he keeps himself informed by evening classes. At all events the oldest method of all, by which an apprentice worked at his craft all day and at his books and evening classes most of the night, was far harder training than the other two methods, it separated out the triers and stayers and certainly produced industrious men, very many of whom, at this moment, hold leading positions; but in all three cases the man with the trained brain has the advantage over the ordinary craftsman. This, coupled with common sense and the art of getting on with his colleagues, learnt at the works, will help a young engineer eventually to reach the top, where we are sometimes told there are many vacancies but few to fill them. The training of marine engineers is a good example of head-and-hand training. A great number of them are now engaged in electrical work, especially in power stations. Their training and work call for quick decisions and self-reliance in times of trouble. They do not wait to ask what to do and how to do it, but do it. Engineers, as the author says, have not taken enough part hitherto in public life, and when one considers that the great engineering projects discussed and legislated for in Parliament, and discussed and voted upon in municipal life by men who are not engineers, one comes to the conclusion that if the engineer will put aside his dread of publicity, train himself for debate and take part in public life, the recognition of his status will be assured.

Prof. F. Bacon: The author pleads especially for consideration of the problem of the finding of real engineers to be trained. I do not dispute his contention that the finding of engineers to train is far more important than the finding of methods of training them, but I remain sceptical as to whether it is possible, or even desirable, to formulate rigid systems of selection at an early age. Reference has been made to tests of intelligence and vocational tests. The only people competent to express an opinion on their value are those who have had opportunities to impose such tests on a number of boys whose subsequent development could be watched. I therefore feel inclined to attach much significance to Mr. A. P. M. Fleming's statement on page 222 to the effect that he did not think there would be much help forthcoming from intelligence tests and the work generally of the psychologists, although one appreciates the attempt made to solve the problem on scientific lines. I also doubt very much whether it is either fair or wise to expect headmasters to determine who should be pushed into, or held back from, the engineering profession. Progressive weeding out from a broad basis of entry is the secret of the Admiralty system of training dockyard apprentices which had achieved such notable results during the last three-quarters of a century. I went to Belgium and Luxembourg last autumn and was interested to observe that those countries select their engineers by methods which involve drastic weeding out, not previous to, but during the process of specialized training. I was informed that about 450 students enter the University of Liége every year to study engineering and mining. The examinations at the end of the first year cut down the number to, say, 120. Further reductions follow at the end of the second and third years, until eventually only about 50 succeed in graduating at the end of 4 or 5 years. Greater strictness in limiting the number of young men who start training to be engineers is only to be desired in so far as it will deflect unsuitable candidates to other callings. It would be a positive misfortune to deter able young men from following such courses simply because the engineering profession might not be able to absorb them. I am strongly of opinion that an engineer's training ought to be regarded as a fine educational equipment for a variety of industrial occupations. The subjects taken at college are vastly superior to many of the miscellaneous combinations of courses taken by those graduating at provincial universities, and a year or two of workshop training ought to prove a valuable asset in almost any walk of life. An overflow from the engineering profession into other callings is something to cultivate rather than avoid, as its consequences should be beneficial both to the community and to the profession. In regard to economics, the need for the study of which has been pointed out, at the Swansea University College a public accountant is voluntarily giving a course on what he calls "the theory of accounts and factory costing," which is being followed with keen interest by the students and staff. The accountant's point of view naturally has great influence with boards of directors, and for this and other reasons it is most desirable that the engineering student should come in contact with it at an early stage in his career.

Mr. H. D. Madden: I should like to associate myself with the general trend of Mr. Allan's remarks. I am in accord with the point made in the paper as to the personal bearing and characteristics of the budding engineer. Administrative engineering training is highly important, and in this connection I favour the public schoolboy, who has learned discipline, knows his place, and has the faculty of earning the friendliness of the workmen, thus securing their co-operation. When he has had some workshop experience he should be sent to college, as by this time he will be more fitted to understand the lectures. Normally a boy does not develop until he is 22 or 23. I am a strong supporter of the Cardiff Technical College, but that institution was not meant to be a machine for turning out engineers by the hundred every year, whether suitable or not. In my opinion, some boys go there who are too young for technical training; they should rather be learning

English and the classics, etc. The time for technological teaching is after the age of 16, when the mind can absorb it intelligibly and intelligently. I have had something to do with the training of engineers for my own branch of the profession. It has taken three years to evolve a scheme of examinations for the different sections, and my remarks are based upon that experience. Some young fellows have a natural aptitude and instinct for research and investigation; these are born engineers.

Mr. H. S. Thomas: The wise man is never too old to learn, and the paper will bear reading again and again. With regard to what Mr. Madden has said as to taking youths into the workshop who want to be engineers, what is more fascinating than watching a blacksmith at his forge? I fully agree with Mr. Madden in respect of putting youths into the works at the outset, in preference to sending them to college first. The handling of men, the study of human nature, is perhaps as important an item as any other in the education of an engineer. I feel that much time has been devoted to stating how an engineer should be educated, but the reference to the necessity of first catching the hare before one can have hare-soup is surely closely analogous to first taking care of having the necessary ingredients for making a young engineer; and when one sees the diminishing birth rate and takes cognizance of the utter disregard paid to the selection of one's life partner, one is struck with the idea that perhaps we begin at the wrong end, and that selection on eugenic principles might be a proper subject for due consideration by the committees who have in hand the matter of the training of engineers. Perhaps, however, this aspect of the subject has already received consideration in the proper quarters.

Mr. P. J. Plevin: I feel that the professional engineer (as distinct from the operative engineer) suffers from the fact that there exists no controlling authority whose license would establish his status. The legal and medical professions form "close" corporations, no members being allowed to practise without licence from their respective associations, which licence is not granted unless the applicant has the necessary professional qualifications. The technicalities of these professions are little known to the layman, who usually takes no interest in them unless he happens to be ill or needs legal advice. Moreover, even though a layman may possess a knowledge of medicine, he would risk a charge of manslaughter were the exercise of his knowledge to lead to results unfortunate for the patient. Similarly, many of the lawyer's functions are such that their performance by a layman is illegal. The profession of engineering, on the contrary, suffers by comparison in that a considerable knowledge of its principles and practice is frequently acquired, and can be exercised without legal risk, by persons who are not engineers by training or profession. When such persons are users of engineering apparatus it is difficult to find any reasonable objection to this condition, since a good workman must be familiar with his tools, and must be able to judge of their suitability for his purposes. None the less, the condition entails on the profession a disability which is not incidental to those of law and medicine, and which constitutes a grave disadvantage to its members. It is, of course, not to be expected that inherent disabilities such as this could be overcome as a direct result of the introduction of a licensing system, but there is no doubt that a system of the kind would benefit the public, in that the employment of a licensed engineer would ensure competent service, and would also help the qualified engineer by improving his status. The science or engineering diploma of a university is recognized by the engineering institutions as exempting candidates for membership from examination, and such a diploma might well form one of the qualifications for licence. Sound practical experience and good character would form other qualifications. Practical experience is, perhaps, a factor even more important than technical qualification, but it takes many years to acquire, and the engineer may reach a mature age before he can expect to obtain his licence and reap financial benefit from the money expended on his training. There is thus all the more reason, if he has ability and is industrious, that he should then have reasonable prospect of a competency. At the present time, on the contrary, there is no profession in which the return on money invested in training is more slow and precarious than that of engineering, and some action to improve its status, especially in respect of remuneration, is urgently needed. When a user of machinery buys a new tool he is guided in his selection by his past experience of the performance of different designs and makes, and selects that which has proved most suitable. If the tool is required for a new purpose of which he has no experience, he will, if he is wise, select one which bears the "hall-mark" of a first-class maker, even though it may be more costly. When he selects an engineer he has little but his faculty of discrimination to guide him, since he cannot assess merit by the criterion of personal experience, and the properly qualified engineer, as things are now, has no generally recognized hall-mark by which he can be identified. If the engineer possessed a hall-mark such as a licence, the task of selection would be simplified, since choice would be confined to licensees. Such a limitation would enhance the status of the properly qualified man, and, as a consequence, his remuneration.

Mr. J. R. Morgan: I have already served an apprenticeship before entering on a college course and I think the arrangement very advantageous in that the student can the more easily correlate theory and practice. First and foremost, the engineer should be a practical man and the possessor of sound common sense. The value of a college course lies not so much in the theoretical knowledge obtained, as in the confidence which it instills in the student, and the ability to apply this knowledge successfully to problems which present themselves in the course of a day's work.

Mr. W. Nairn: There is one duty of the engineer which does not receive the attention which it deserves, and that is the duty of looking after his health. Many engineers work too long hours and smoke too much, with the result that their constitutions are gradually undermined and they thus become unfitted for the calm consideration of labour problems and engineering emergencies. The author refers to the duty of culti-

vating courtesy and humour; both these qualities come naturally to the healthy man.

Mr. S. B. Haslam: I am altogether in agreement with Mr. Madden as to the value of a public school training. It is an old saying that no man can command unless he can be commanded, and the discipline a boy receives at a public school, not only from those in authority, but also from the other boys, will serve him well throughout the whole of his life; it can be summed up in the expression "playing the game." I am very interested in the remarks that have been made as to the specialized efforts being carried out by certain headmasters with the object of discovering the trend of a boy's mentality while at school, but I would go even farther and suggest that it is quite possible to find out very much earlier in life whether boys have engineering brains. Motor-cars, motor-cycles, and even Meccano sets could be used with this object. The question of the rotation of the practical and theoretical training is always a controversial one. I quite agree with Mr. Madden that it is desirable for the practical side to come first, and that the "sandwich" system is the ideal one. It makes the theoretical side much easier if the student knows, from his practical experience, what the theorizing is about. The late Mr. T. Hurry Riches, one of the leading experts in technical education of his day, was very emphatic upon this point. Although I sympathize with the diploma-of-admission idea, I do not think it is possible in our profession. There is no profession in the world which offers such an opportunity to what I might term, for want of a better expression, the "rankers." Ordinary technical education that is available both in evening classes and in the "sandwich" course, opens up the highest posts in the profession in a way that cannot be equalled in any other profession, and it must not be forgotten that some of the leading engineers of the world would never have got into the profession at all if they had had to sit for an entrance diploma.

Mr. W. Cleaver: Although I have as much admiration as anyone for the real born practical engineer of the old school, there is very little excuse for these to-day. With the existing facilities for gaining technical knowledge at colleges and universities, every young engineer should be well equipped with the kind of theoretical training which, in combination with the still unavoidable (and one may almost say the "primary requisite") practical training, makes the successful engineer of to-day. Trouble is, however, in my opinion usually experienced through too much cramming on the one hand, and on the other hand the unattractive way in which theoretical knowledge is usually taught in most colleges. The high-sounding terms and phrases, used generally without any clear or analogous explanation, more often than not frighten the average student at the commencement, just when it is most necessary to interest him; and in that sense I think it would be well if many of the engineering professors, lecturers, etc., would read and digest the preface to the first edition of Trautwine's "Civil Engineer's Pocket Book." In my opinion the principle inculcated somewhat concisely in that preface still holds good, and is deserving of wider application and repetition. I quite agree with the author in his remarks in regard to the necessity of impressing on all students the necessity of acquiring self-confidence, and in fact the advisability of sometimes taking risks, so long as any more or less indeterminate work undertaken is always based on the consciousness of sound knowledge of principles.

Mr. V. Harrison: I consider the "sandwich" system of training to be the ideal one, but before youths are permitted to enter the profession they should be called upon to submit to an examination, the nature of which should be decided upon by the engineering profession. This would serve to eliminate at the outset many who have no aptitude for the profession. A safe guide to a boy's bent is enthusiasm; if he is enthusiastic about his work it will carry him far.

Mr. J. W. Burr: One reason why engineers are not taken at their true value is that they are too prone to depreciate themselves. If engineers have need for a religion it is set down on page 193: "This, then, is a proper life: a constant giving and receiving, a perpetual interchange of services, ideas, and commodities, with an unfailing consideration of our neighbour's good as well as of our own, and a constant recollection that those who forget their common obligations, and merely demand their own due without caring what happens to others, are the slayers of the nation's soul."

Prof. G. Knox: I am entirely in agreement with the author when he emphasizes the fundamental principles that go to the formation of character, so essential to success, in the widest sense of that term. It is true that knowledge and the ability to apply it may, without character, be a danger instead of a blessing. It is in this respect that teachers can be helpful in shaping the future of embryonic engineers in their preparatory, vocational and technical training. It cannot, however, be too often stated that the teaching of science can be adapted to the formation of character as well as in the case of classical training. Mr. Gregory's admirable work "Discovery" may be quoted in this respect. He says: "Do you wish education to cultivate supreme regard for truth? Then let it include the study of Nature, for in dealing with her every false coin is inexorably nailed to the counter. Do you wish to create a sense of moral responsibility? Then learn from Nature that every act has a consequence and every sin a penalty. Is a habit of mind required which will not be deceived by the noisy huckster of sensational statements? Then give attention to training in scientific method, by which a critical faculty is developed that enables fact to be distinguished from fable and is cautious in arriving at conclusions. Do you believe in the dignity of work and the duty of self-sacrifice? Then turn to science which demands devoted labour for the benefit of others. Are satisfaction with the superficial and a desire for continuous excitement to be the characteristics of the new generations? If not, see that interest is aroused in the nobler views of life opened by scientific knowledge. Regard for veracity, patience, logical thought, responsibility, discipline and original work are all taught by the study of science, and those attributes are as desirable in every one of us as in the investigator whose life is an exemplar of them." The modern idea of all education is based on the fact that human (or social) progress is mental progress, and consists in the preparation of the in-

dividual for an understanding of and willing co-operation in the world's affairs. But, according to Earl (A. J.) Balfour, "science is the great instrument of social change—all the greater because its object is not change —and its silent appropriation of this dominating function amid the din of political and religious strife is the most vital of all the revolutions which have marked the development of modern civilization," and "the scientist has his hand on the throttle valve of this instrument of social change." In the selection of the potential engineer much may be done by intelligence and vocational tests to overcome the haphazard choice, whether from "birth" or "accident," but in most cases wider experiments are necessary to enable the student to make his final choice. It is no uncommon thing for students (from public and other schools) entering technical colleges to be trained as engineers to be without the slighest understanding regarding the phase of engineering for which they are best adapted. As an example of what frequently happens, three applicants for entry in the chemical engineering course at the South Wales School of Mines gave as the reason for their choice that chemistry was the only practical subject taught in their respective schools. On being offered and accepting a few weeks' experience in engineering works they all decided that they would prefer to be mechanical or electrical engineers. They were then given an opportunity of spending a few weeks underground at a colliery and two of them decided to be mining engineers; the third hesitated between mining and electrical engineering, but chose the latter owing to objections which his parents had to his taking up mining engineering as a profession. All three have done well in their educational training and show signs of becoming successful engineers. They are also very grateful for the advice tendered and the opportunities granted them to choose careers which interested them more than the one originally chosen. Having determined that the youth is going to be an engineer, his course of training becomes the next consideration, and here again care must be taken to distinguish between the two types of apprenticeship, because the career of an apprentice differs fundamentally from that of a "pupil," in that skilled handicraft rather than proficiency of brain power forms its basis. This must not, however, be taken to imply that the embryonic skilled craftsman must necessarily be of lower mental calibre than the pupil—although many of them may be —but it makes it essential that provision be made for the transfer of the apprentice to the pupil class where the former shows the necessary ability to profit by it. There is a large measure of agreement to-day among both industrialists and technologists in accepting the sandwich system as the most suitable method of training youths to fill official posts in industry, where practical experience combined with technical training is required. When compared with the college as post-works training, or the works as post-college training, the sandwich system has many advantages: the pupil has no break in his educational career and therefore does not forget how to learn or what he has already learned. His general knowledge of workshop appliances makes it easier to instruct the pupil in technical processes, and the work becomes more interesting. The pupil obtains all the practical and humanistic value attached to mixing with his fellow workmen. This establishes human values in his mind and enables him to determine accurately the value and quality of work done. In the later years of pupilage in passing through the official departments he learns the value of order and discipline, and in alternating school periods is taking an active part in the management of his own students' association. The pupil is also advised how by tact and patience he can obtain the knowledge gained from experience of those with whom he associated when employed at the works. He thus acquires a knowledge of character and human understanding which assists in developing that executive ability so necessary and yet so often lacking in engineers. He is also encouraged to question the solution propounded to every problem, and not to take anything for granted without inquiry. He is thus taught that self-reliance is essential before he can accomplish self-direction, and that both are essential in the cultivation of initiative, without which he could never be trusted with large responsibilities. I quite agree with the author that to memorize results is useless as training. A college is a place in which to learn fundamental principles and accuracy in thinking, working, observing and classifying, and not to acquire merely purely technical details. It is the duty of the college to provide the student with an intellectual equipment which, with the aid of experience, as he advances in his profession, will become more and more useful to him, rather than provide him with the details of present-day practice which very soon get out of date. To obtain the best results from any scheme of educational training, contact with the industry and the closest possible co-operation between the college and the industry of the district are absolutely essential.

Mr. C. G. Bevan: With regard to the finding of engineers, the profession of a youth is generally settled by economic causes in connection with his family, and if he has common sense and a trained character he will be a success in any profession irrespective of his bent. Otherwise how would recruits be obtained for professions such as "dental surgery," which cannot of its nature be attractive? Personally I consider that engineering loses fewer of its born members than any other profession; the entrance to the engineering profession is so wide that more undesirable recruits are gained than good men rejected. Who is to be made responsible for their rejection? With a full-time student who has come from a secondary or public school, it is possible that, even if admitted, his performance during the first year's course may be sufficient indication to himself or his parents as to whether or not he has chosen wisely. A technical college, however, usually has to deal with young men who have already chosen their vocation and are definitely apprenticed. It is obvious that those responsible for their training could often give excellent advice on the interchange of particular youths in their selected spheres, but I cannot regard the possibility as being in any way practicable. We can hardly do more than advise a student as to which branch of the profession he should aim for—provided he has such a choice. Referring now to section (6) of the paper, since the world we live in is so highly dependent on the engineer and his products, it certainly is strange that he takes so little

part in public affairs, especially when one notes the similarity of capital and labour, and heat and energy, or taxation for wasteful relief or excessive interest with a wattless current. I can imagine no one whose opinion on everyday problems would be of more weight than that of a charge engineer of strong and sympathetic character. His knowledge of costs and output, handling of men, plant and material, and accurate and quick decision in times of emergency should be of the utmost use to a nation.

Mr. T. Stretton: In his opening remarks the author has, with admirable outspokenness, recorded opinions and ideas which many people hold but have not the courage to voice. If it were only possible to put into actual operation a law whereby the fittest to live were allowed to survive, what a much more efficient race of people we should be. However, as it is useless to strive after impossibilities we must make the best of the world as it is. Under section (3) the author stresses the necessity of selecting children for the engineering profession at an early age, and with this I agree, but he goes on to suggest that this selection should be part of the duty of a teacher. With this I entirely disagree. My own experience teaches me that the natural propensities of a child towards any particular sphere of activity are much more apparent to the parents than to the teacher, and, therefore, the parents are in the best position to decide on the proper sphere for their children. Mistakes must be made, but I believe they are made less frequently by parents than by teachers, and naturally so. Under section (4) I should have expected the author to lay stress on the vital necessity of learning to speak in public as part and parcel of the training of an engineer. That it is a vital necessity no one will dispute, but sufficient encouragement and opportunities are still not given to the young engineer. Matters are certainly improving in this direction, but that the engineer is not found to any great extent in public life is, in my opinion, due to his inability to voice his ideas in public. Has an engineer been Prime Minister of this country? I think not, and the only possible reason is the one I have stated—there can be no question of his ability to fill that high office with credit to himself and to his profession. A question we must ask ourselves in connection with the training of an engineer is: Are we becoming too specialized? It is agreed that, as regards early education, the ideal is a system arranged to suit the special requirements of each individual, but I believe that the specialized pupil is apt to be turned out too highly insulated for the current of everyday life. Take our engineering institutions and associations—their name is legion, and they are multiplying daily without being fruitful. To those young engineers who may wish to extend their knowledge by belonging to more than one specialized institution, the gates are closed owing to the expense entailed. Why should there not be one great engineering institution with sections devoted to the various branches of engineering? A moderate subscription and an enormous membership would enable such an institution to raise the status of an engineer to at least that of other professions, which have far less justification for existence than that of the engineer to whom the progress of the world is mainly due. There would result a far greater interchange of ideas amongst the members of the various sections, and I believe this would be of inestimable benefit to the young engineer as well as to the old.

Mr. W. Roberts: One aspect of the paper which is of very great importance, but is in these days insufficiently stressed, is the fact that there is no right without a corresponding responsibility. The whole trend of legislation for the past 25 years has been to do things for the individual without exacting anything in return, and an engineer who is by nature fitted to see the essential fallacy of perpetual motion should be the type of man to appreciate that, just as it is impossible to obtain output without input, so it is impossible to expect a well-balanced individual when all is taken and nothing given. The community demands an equal proportion of impression and expression, and looked at from this point of view the engineer should be more fitted to take a greater part in public work than he has done up to the present.

The Author's Reply to the Discussions at Dundee and Cardiff.

Mr. T. Carter (*in reply*): These last two discussions follow largely the same lines as the earlier five already replied to; and I would say here, as before, that if I do not specifically mention the name of every contributor, or deal individually with all the points that were raised, I hope it will at least be found that I have so caught the essential spirit of the discussions that my reply is adequate. Some parts of the paper were again more commented on than others, but there is scarcely any part that was not referred to in some way. Thus further evidence is afforded of the real place that the whole subject has in the common thought of engineers, perhaps mostly unexpressed in words; and once more I suggest that the Engineering Joint Council, or, failing that body, the several engineering Institutions, might well examine very closely the question of how to use our human resources adequately. Mr. Stretton suggested the possibility of one great engineering Institution with a section for each branch of engineering; I am heartily with him there. The Engineering Joint Council is a possible nucleus of the Council of the Institution of British Engineers, which is the body that Mr. Stretton wishes to see established. At present, according to Article 4 of its Constitution, the Engineering Joint Council may not initiate proposals, and is only an advisory body without executive powers; but, just as not very long ago the existence of even this link between the constituent Institutions might have been thought impossible, so it may not be very long before some closer union is achieved. The present Institutions would be the sections, each having its own Council with executive powers limited only by the constitution of the general body; and the general body would take care of the interests of the whole profession of engineering. One of the important questions with which it would doubtless deal is that of status, to which so many

speakers referred in the discussions. The status of a profession in the eyes of the community must always depend on the general effect of the profession's activities. It is obvious, for example, that members of the Institution of British Burglars, were there such a body, would not be greatly cherished by the community, except so far as the occasional provision of food (plain but wholesome), clothes (adequate for covering but not made to measure), and shelter (in a place that is weatherproof but terribly dreary), might be described as cherishing them. Height of regard is commensurate with extent of proved service; and on no other foundation can it in the end be built up. Even so, it seems to be necessary to exert organized effort to secure a proper return for services rendered; there are not many people who eagerly rush to pay an account before it is sent in. So, surely, the Institution of British Engineers could well do for engineers what the General Medical Council does for doctors. In order "to enable persons requiring medical aid to distinguish qualified from unqualified medical practitioners," the General Medical Council of Medical Education and Registration was set up under the Medical Act of 1858, and thus both the scientific and—shall I say?—the industrial interests of the profession are within its province. Similarly, in the legal profession there are the General Council of the Bar and the Council of Legal Education for barristers, the one having executive powers to deal with all matters affecting the profession, and the other superintending the education and examination of students; the Law Society for solicitors, controlling the education and examination of articled clerks and the admission of solicitors in England and Wales; and other corresponding bodies in Scotland and in Ireland. So a General Engineering Council might weld all British engineers into one Institution, and might confirm the status they had built up for themselves and secure the rights they had acquired because of their services to their fellows. Education is already seen to by the individual Institutions; but co-ordination of education by the General Engineering Council would doubtless be valuable. Registration of engineers, corresponding to the other part of the duties of the General Medical Council, has not been widely undertaken, though some sections, such as the electrical contractors, have already established it for themselves. I take it that the General Engineering Council would be bound to see to that; and here I must mention a notable attempt to put the proposal for the registration of engineers into words, namely, the Bill drafted, if my information is correct, by the Society of Technical Engineers, and introduced into Parliament on the 29th April, "to provide for the registration of and to regulate the qualifications of engineers." Whether or no registration comes in such a way as the Bill suggests, it would seem to be one of the next great steps in engineering politics; and the advantage of the Bill is, if no more, that it gives us something concrete to discuss. It will be seen by those who refer to it that it contemplates the setting up of a "General Council of Engineering" having the duties indicated in its title. I would hope that the General Engineering Council, which I have suggested as the unifying body for all the engineering Institutions, would be allowed to go further, and would be endowed with power to deal with and take action on all matters affecting engineers. Whatever its ultimate fate, the Bill now before Parliament may become a lasting landmark in the history of the profession.

It is largely because of what may be called the unestablished position of the profession that engineers have been too feeble a force in shaping the course of public life; their possibilities of individual and corporate usefulness do not come naturally to the public mind. As I write, I have at my side a copy of *Engineering* for the 9th July, the leading article in which, dealing with industrial statistics, points out that the Committee formed some months ago to collect and publish information about manufacturing operations "included employers of labour, trade union leaders, and experts on economics, accountancy, and law," and then makes the following useful comment: "Curiously enough, or perhaps we should say characteristically, no provision appears to have been made for the representation of the technical personnel, which by position and experience is particularly well qualified to deal with the questions involved. The opinion, long prevalent in the country, that the conclusions of the scientific and technical expert should be given to the public solely at second-hand, through men having what Mr. Webb has called characteristics suited to government, dies hard." Characteristics suited to government are far more acquired than inborn; and men will not have them until they are allowed to train themselves into the proper habit by practice. For a body so vital to civilization as the whole body of engineers to have so little a part in the counsels of the nation is an anomaly that must be corrected; and an established position, however attained, is certainly one of the first requisites, if not the very first. I am glad that Mr. Stretton specifically mentioned the value of learning to speak in public, which was implied to some extent, but not definitely enough expressed, in what I said in the paper about the necessity for the accurate use of words; it has an important bearing on the whole question of public influence, and it would help to counteract the tendency to self-depreciation deplored by Mr. Burr. My last word here on this great subject of the establishment of the profession will be that the very variety of personalities included under the general term "engineer" will perhaps make it immensely difficult to define the boundaries of engineering; but, particularly in the view of engineers, difficulties exist only to be overcome.

Recalling, in passing, Mr. Thomas's interesting but, I fear, very controversial eugenic suggestion, I must now turn to other matters. Difference of opinion on the age at which it is possible to ascertain the bent of a human being, and on the agency or agent through which or whom it is to be ascertained, leaves untouched what seems to me to be general agreement on the advisability of somehow ascertaining it. There seems to be much distrust of the head master or the teacher as the agent; and here I can only express again my view that while many teachers at present have no inkling of how to make the discovery, many parents have just as little, and both will need to realize the problem as they do not now before they can co-operate with each other. That is what I intended to suggest in the paper;

not that one or the other should decide alone, but that all the results of observation, from the very different points of view of parent and teacher, should be used for the good of the persons observed, be they infants, youths, or older men. Prof. Bacon shares Mr. Fleming's fear that we shall not get very much help from the schoolmasters; but I regard his objection quite frankly as one that will be found to be invalid when we have gained more experience. In sorting coloured wools, we begin with a general division of the bulk into a few large classes, and it is not until we become quite expert that we can distinguish the finest gradations of shades. The analogy is far from perfect, but it has some bearing; let us begin to classify broadly, and see whether finer distinctions will not soon be evident. To question whether a thing can be done is the way to prevent its being done; but that is not a scientific attitude. Philosophic doubt may lead to so nice a balance of possible choices that the doubter is paralysed; scientific doubt is a stimulus to discovery and achievement. Look, for example, at the work of the Dundee Sub-Committee described by Mr. Frain; look at the work being done by Dr. Johnston at Highgate; and do not imagine that there is anything in the atmosphere of Dundee or of Highgate that makes miracles possible in either place. Could any miracle happen in unromantic Dundee? The difference is (and perhaps, after all, this is a miracle) that people are found there who not only have seen a need and made a resolution about how to deal with it, but have carried out their resolution and begun to meet the need.

Here is a fable of "The Hill," told by Laura E. Richards: "I cannot walk up this hill," said the little boy. "I cannot possibly do it. What will become of me? I must stay here all my life, at the foot of the hill: it is too terrible!" "That is a pity!" said his sister. "But look, little boy! I have found such a pleasant thing to play. Take a step, and see how clear a footprint you can make in the dust. Look at mine! Every single line in my foot is printed clear. Now, do you try, and see if you can do as well!" The little boy took a step. "Mine is just as clear!" he said. "Do you think so?" said his sister. "See mine, again here! I tread harder than you, because I am heavier, and so the print is deeper. Try again." "*Now* mine is just as deep!" cried the little boy. "See here, and here, and here, they are just as deep as they can be." "Yes, that is all very well," said his sister; "but now it is my turn; let me try again, and we shall see." They kept on, step by step, matching their footprints, and laughing to see the grey dust puff up between their bare toes. By and by the little boy looked up. "Why!" he said, "we are at the top of the hill!" "Dear me!" said his sister. "So we are!"

Prof. Bacon, Prof. Knox, Mr. Bevan, and others referred to the weeding-out of unsuitable persons. To Mr. Bevan's question, Who is to be made responsible for the rejection? the answer of the future will be, I am sure, the General Engineering Council; meantime let us try to create such a body. Prof. Knox gives exceedingly interesting examples of skilled guidance of students from preparation for a less suitable to preparation for a more suitable career, again showing what can be done when the right man does it; and Prof. Bacon instances the procedure at the University of Liége as showing how weeding-out may proceed. But what I wish he had stated is what becomes of the 70 students weeded out in the second and third years. It is quite true, as he says, that an engineering training is a fine thing for anyone; but not everyone can afford it, and if out of 450 students who begin only 50 finish the course, some at least of the 400 who drop out must be handicapped for other means of livelihood by their delay in getting to the right thing. It all goes to show how essential it is to discover the dominant tendency at the earliest possible age, using all likely ways of doing it. If we say "earliest possible," and leave it at that, we may avoid controversy on what the age is to be, and, as in Dundee and at Highgate, we may even begin to discover the tendency for ourselves. I am still of the opinion that it would be well to reduce the number of those who become engineers; but that, as Prof. Bacon will agree without hesitation, has nothing at all to do with restricting the number of those who take an engineering training because it is a fine equipment for some other industrial occupation.

On the whole, the discussion seems to show a preference for the sandwich system of training engineers, as more likely than others to preserve the capacity for intellectual edification while not neglecting the contact with people and their habits in works that is so essential for a right understanding of the administrative side of an engineer's duty. Prof. Knox emphasized a vital point when he stressed the need for close co-operation between the college and the industry of the district; and what I know of the South Wales Electric Power Distribution Company's training schemes makes me think that they meet the need in an eminently useful way.

Noting, in passing, Mr. Nairn's valuable hint as to health, Mr. Cleaver's reminder of the absolute necessity of understanding at least the probable underlying principles before any new kind of work is attempted, and Mr. Stretton's regret, which everyone shares, that it is almost impossible nowadays for any of us to keep our knowledge as wide as we should like it to be, I must next pause to draw special attention to Prof. Knox's reference to education as a preparation of the individual for an understanding of the world's affairs and a willing co-operation in them, and to quote beside it something said by Dr. Jacks in his book "Realities and Shams." "The educated man is, before all else, the man who understands everything about his own work, and enough about other people's to enable him to co-operate with them intelligently in the social complex. *Per contra*, he who understands everything about somebody else's work . . . and next to nothing about his own, may well stand as the type of the uneducated man. . . . The only happy man is the man who enjoys daily work, and the only good man is he who does it to the best of his ability." Marcus Vitruvius Pollio, a Roman architect and engineer who wrote a book called "De Architectura" about 2 000 years ago, demands from the engineer a variety of qualifications that shows, if it is legitimately demanded, how difficult it is for him to understand everything about his own work. "The

engineer" (I quote from *The Arc* for July, 1925, published by Messrs. J. Halden & Co., Ltd.) "should be a good writer, a skilful draughtsman, versed in geometry and optics, expert at figures, acquainted with history, informed in the principles of natural and moral philosophy, something of a musician, not ignorant of the sciences, both of law and of physics, nor of the motions, laws, and relations to each other of the heavenly bodies. Moral philosophy will teach him to be above meanness in his dealings and to avoid arrogance. It will make him just, compliant, and faithful to his employer, and, what is of the highest importance, it will prevent avarice from gaining an ascendancy over him; for he should not be occupied with thoughts of filling his coffers, nor with the desire of grasping everything in the shape of gain, but by the gravity of his manners and a good character should be careful to preserve his dignity." Here is something for us to live up to!

In connection with the matter of the accurate use of words, I must refer to some books that I have found of the greatest possible value. These are: "The King's English," by H. W. Fowler and F. G. Fowler; "The Concise Oxford Dictionary," by the same authors; "A Dictionary of Modern English Usage," by H. W. Fowler; "The Sounds of Standard English," by T. Nicklin, M.A.; and "Speaking," by William Mair, D.D. All are published by the Clarendon Press except the last, which is published by William Blackwood and Sons; the first three are particularly useful as guides in composition, while the last two are intended as aids to correct utterance.

I hope that the information given by Prof. Bacon about the valuable work of the public accountant at Swansea University College will be noted, and that similar service will be rendered in other places to those who may have no other opportunity of getting a sound knowledge of economics. It is so obvious as scarcely to need mentioning, that if only all those who guide the many parties associated in engineering could be told the full story of the dependence of everything upon everything else, there would be fewer party slogans to mislead, and more frequent common efforts to strengthen every member of the engineering body, whose health depends on the co-ordinated activity of all its parts. A famous schoolmaster hoped at the end of his days that he might not have harmed the boys who had been in his care; what might not our gain be if we all, small and great, went through life in the same fearful spirit?

In an address delivered over telephone wires from New York to the Pacific Coast Convention of the American Institute of Electrical Engineers at Seattle on the 17th September, 1925, Dr. M. I. Pupin, then President of the Institute, pointed out how, shortly after the American Colonies separated from Great Britain, George Washington's engineering instinct caused him to suggest that a meeting of commissioners from all the States, at that time by no means united, should be held to consider a national question, namely, the navigation of territorial waterways. The discussion of this engineering problem in a way suggested by an engineer was thus begun, and was adjourned to another meeting to be held at Philadelphia in 1787. This eventually became the Federal Convention in Philadelphia, at which, under Washington's presidency, the Constitution of the United States was framed. Political chaos and thoughts of individual sovereignty gave place to political order and a recognition of the need for united effort; and thus, as Dr. Pupin said, "the resourcefulness of the engineer . . . helped to save the situation at the most critical moment in the early history of the United States." There we have one side of the engineer's influence on public life, given a great opportunity and a great man to use it; the other side, the haphazard and dreary result of visionless throwing together of bits and pieces, is typified in a sentence written, I think, by Michael Arlen: "Now and then an omnibus rolled by, rolled on, and on, and on, the red-and-wite monster born of man's divine gift for making his life intolerable."

Although the paper is little more than a series of pegs to hang discussion on, it has at least brought together a company of kindred souls to think for a moment or two of fundamental things; and who knows what far-off ends may not have their beginning here? The ebb and flow of night and day monotonously following night and day will wear us down to a dull flatness if we do not escape now and again from immersion in details to some vision of wider spaces. Only so shall we preserve a lively hopefulness and save ourselves from passive acquiescence; only so can we be moulded to a finer shape. What we pass through counts for nothing unless we come out of it cleansed and strengthened; that is everything. The most that we can discover is but a little here and there in the great universe; and yet some of our seeking is not in vain. Let us hold fast what we find, and be glad that amongst much dross there are at least a few specks of gold. Treasuring these, we shall never cease to search for more; and thus our life shall find noble expenditure until, as night falls, we lay down our work and go to rest.

DISCUSSION ON
"AN ALL-ELECTRIC HOUSE." *
SUPPLEMENT TO THE AUTHOR'S REPLY.

Dr. S. Parker Smith (*in reply*): Tables J and K below show a comparison of the results obtained in the first and second years for the all-electric house (10 rooms) with six persons in the house, excluding guests.

First year (52 weeks): 12th July, 1924, to 11th July, 1925.
Second year (52 weeks): 11th July, 1925, to 10th July, 1926.

TABLE J.

Total Consumption in Units Recorded on Main Two-Rate Meter, and Cost.

	First year				Second year			
	Units	Cost			Units	Cost		
		£	s.	d.		£	s.	d.
Fixed charge ..	—	12	10	0	—	12	10	0
Day load at ½d. per unit ..	10 299	21	9	2	9 713	20	4	8
Night load at ⅜d. per unit	6 043	9	8	10	5 827	9	2	1
Total for year	16 342	43	8	0	15 540	41	16	9

Cooking.—The only noteworthy change is in the reduction of the consumption for cooking. With the original cooker with open-type boiling-plates, the average weekly consumption over 35 weeks was 60·3 units. With the new cooker with utensils with self-contained elements, the average weekly consumption over 17 weeks was 25·4 units, with a maximum of 30 units. Thus cooking with self-contained utensils not only gives the required celerity and safety, but reduces the daily consumption per person to 0·6 unit.

Reliability.—It is satisfactory to report that, from the time of our entering the house, the supply has not once failed.

Troubles.—Beyond the initial inconvenience of sorting out good from bad appliances, and the development of a satisfactory cooker, the only trouble worthy of mention is that arising from the use of flexible cables. These have now been abolished with the cooker. A periodic inspection of all flexible cords and cables is desirable. The flat-iron is the chief offender, and on one occasion a bad burn resulted from a broken wire. Though the iron can scarcely be called characteristic of an all-electric house, it emphasizes the need for a satisfactory solution of this problem of flexible cords and cables.

TABLE K.

Analysis of Consumption in Units.

Separate meters	First year	Second year	Remarks
Heating ..	5 954	6 636	Increase due to severe winter
Hot water, day	1 242	1 245	—
Hot water, night	6 043	5 827	—
Cooking ..	2 777	1 858	Decrease due to self-contained utensils
Lighting ..	568	687	Increase due to larger lamps
Total	16 584	16 253	
House closed ..	19 days	10 days	

* Paper by Dr. S. P. Smith (see pages 289 and 777).

PROCEEDINGS OF THE INSTITUTION.

739TH ORDINARY MEETING, 18 FEBRUARY, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 4th February, 1926, were taken as read and were confirmed and signed.

Messrs. H. W. Hartridge and E. Ambrose were appointed scrutineers of the ballot for the election and transfer of members and, at the close of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Member.

Robinson, James, D.Sc., Ph.D.

Associate Members.

Amos, William Josiah.
Busbridge, Horace Claude.
Scherman, Elie.

Graduates.

Avis, William John.
Blythe, George Edward K., B.Sc.
Brown, Harry.
Calver, Frank Norman.
Clayton, John Richard.
Dass, Amendranath.
Evans, William John.
Fisher, John Philip.
Garrett, Percival Theodore.
Haines, Harold.
Humphreys, Harold Victor.
Hutton, William Alfred, B.A.
Orchard, Patrick Connelly.
Pradhan, Gopinath Krishna, B.Sc.
Simms, Thomas Lowndes, B.Sc.(Eng.).
Weir, William.
Wood, Charles Frederick.

Students.

Aldis, Ronald Edward.
Allworth, Spencer Leigh.
Anslow, Frank.
Aziz, Abdul.
Ballard, William Edwin.
Barry, Henry.
Beaney, Cyril Ernest.
Best, William Bernard.
Billson, Frederick William.
Bond, Foster William.
Bond, John Harold.
Bradley, William Edward.
Brown, Philip.
Buckingham, Leonard Joseph.
Burchfield, John Ernest.
Burrows, Herbert Felix.
Callingham, Walter Sidney.
Carter, John.
Catt, Roland Charles.
Charles, Geoffrey Russell S.
Clouston, Charles Edward.
Cundell, Humphrey Heywood.
Dastidar, Nagendra Nath G.
de Fernandeze, Josie Augustine A.
de Thalis, Vincent Tudor.
Duncan, Maurice John.
Dutt, Sukumar.
Eayrs, Percival George W.
Edwards, Cecil Herbert L.
Elsom, Leonard Ernest.
Elworthy, Bernard Charles T.
Ezekiel, Maurice.
Fairbotham, Lionel Victor.
Faux, Frank.
Ferris, Sidney Herbert.
Field, Douglas Conan, B.A.
Fisher, William Garrow.
Fletcher, Fred.
Forster, Ernest William.
Francis, Cyril John.
Gardner, Victor Albert.
Gethin, Ernest Lewis.
Gourlay, Colin Alfred G., B.Sc.
Grundy, Eric.
Haigh, Leslie Baines, B.A.
Harwood, James Stanley.

Students—continued.

Hoare, Edmund.
Hollander, John Michael.
Hunter, John Garner.
Jarvis, Raymond Frederick J.
Jenkins, Cyril James H.
Jones, Geoffrey Charles.
Joyce, Richard Charles W.
Justice, Charles Reginald.
Kashyap, Harivansh Lal.
Kennedy, Reginald Patrick.
King, Stanley George.
Leigh-Sarney, Harvey Frederick.
Leitch, John Muir.
Lewis, William Emlyn.
Long, Frederick Charles.
Lovatt, Gordon Harold V.
Lusk, David.
McCabe, Ernest.
McCulloch, Robert Percival.
McLaughlin, Cecil Francis.
Mandahr, Narain Hans R.
Meyer, Leslie William.
Middleton, Leslie H.
Mills, Christopher Stanley.
Morse, Clifford.
Nixey, Dennis Edward.
Nottage, Wallace George.
Park, Robert Thomas.
Parker, Harry.
Parrish, Harry John.
Patel, Jashbhai Gouindbhai.
Patel, Kantilal Chaturbhai.
Payne, George.
Peck, Cuthbert Fielding.
Pegg, John Edwin.
Percival, Raymond Edward.
Richards, Percy.
Risso, Arthur Eladio.
Roberton, James Samuel P., B.Sc.
Rose, Lewis Campbell.
Rusby, Hermann.
Scott, Robert.
Sears, Herbert William.
Shoults, Norman George.
Simmonds, Nevil Reginald J.
Skillman, Thomas Samuel.
Smith, Eric.
Sproul, Charles James.
Stentiford, Wilfrid John.
Stockwell, Reginald William.
Sturman, Edward Albert.
Thomas, David Frank.
Thompson, John Leslie.
Thorn, William Alfred J.
Thornton, Cyril.
Thorpe, James Rothschild.
Todd, Donald Walter.
Tompsett, Francis John.
Thornley, Ernest Joseph.
Vatcha, Shiavux Bejonji.
Vincent, Horace John.
Vyas, Baldevbhai Motiram.
Walker, James Roy.
Ward, Charles Geoffrey.
Watts, John Lea.
Way, John Christopher.
West, Francis Richard J.
Whittaker, Douglas, B.Sc.
Whyte, Cyril Leonard A. le B.
Wilkins, Arnold Frederic.
Williams, Alan Cyril O.
Winstanley, William.
Winter, Francis Edward.
Wray, Walter Dean.

Associate.

Hoyle, Harry.

TRANSFERS.

Associate Member to Member.

Bairsto, George Edward, D.Sc., D.Eng.
Brown, George John L.
Cleaver, Richard Lovell, B.Sc.(Eng.).
Dania, George.
Jenkins, Daniel, M.Sc.Tech.
Lazarus, Edmund George.

Graduate to Associate Member.

Amerasinghe, Richard Peter.
Hortop, Cecil Lawrence.
Kaempf, Emil.
Macarthur, Neil Brown, B.Sc.
Pennington, John Hawley.
Wakefield, Paul Stuart, B.Sc.
Wilkins, Cecil.

Student to Associate Member.

Bainbridge, Stanley Rendle.
Baker, John Henry, B.Sc.(Eng.)
Barraclough, Alfred.
Gallizia, Enrico.
Garwood, Godfrey Thomas, B.Sc.
Tustin, Arnold, M.Sc.
Wilck, Charles Augustus.
Wilmshurst, Arthur Percival.

Student to Graduate.

Addison, Joseph.
Allen, John William.
Bader, Ernest, Lieut. R.E.
Barnes, Wilfred Charles.
Bearcroft, Hubert Percival.
Booker, William Mason.
Busby, Arthur Henry W., B.Sc.
Butterley, Archibald Donald.
Church, Leonard Phillips.
Crompton, Oswald James, B.Eng.
Crosbie, Sydney.
de Kretser, Horace Egerton S.
Ferguson, John Donald.
Grech, Vincent Owen.
Gregson, William Herbert, M.Eng.
Grundy, Geoffrey Earnshaw.
Hardaker, Ernest Victor, B.Sc.
Hardy, Alexander Edward.
Harrison, Arthur Casswell.
Healy, John Quarry.
Hegazy, Hamed Mahmoud.
Holder, John Eric D., B.A.
Hook, Herbert James.

Student to Graduate—continued.

Howse, Henry Arthur G.
Hunter, Charles Moore.
Kellie, John Gordon, M.Eng.
Lackie, Donald Walker.
McAinsh, Neville James.
McCarter, Alan Lailey.
Meneze, John Arthur.
Metcalfe, Percival Ignatius H., B.Sc.
Morton, James.
Perkins, James William.
Pewtress, Noel Cecil.
Pistorius, Leo Henry.
Price, Arthur Conrad, B.Sc.(Eng.).
Redclift, Ronald David.
Rodrigues, John Rosario.
Roulson, William Percy.
Ryle, Peter Johnston, B.Sc.(Eng.).
Shishini, Mahmoud El, B.Sc.Tech.
Smith, Cyril Blake.
Srinivasan, Mandayam, Thondanore, B.E.
Stevens, Sidney George, B.Sc.(Eng.).
Taylor, Horace.
Thavenot, Joseph Raymund.
Thomson, Alexander Stuart, B.Sc.
Tingle, Howard Grantley.
Turner, Wilfred.
Walker, Allan Matthias.
Wheeler, Edmund Frank.
White, Sidney Robert.
Wiliams-King, Evan Baker.
Williamson, Peter Blanche, B.Sc.

A paper by Mr. H. Parodi, entitled "Electrification of a Section of the Orléans Railway," was read, on behalf of the author, by Mr. Roger T. Smith, and was discussed.

On the motion of the President votes of thanks to the author, and to Mr. Roger Smith for reading the paper, were carried with acclamation, and the meeting terminated at 8.10 p.m.

52ND MEETING OF THE WIRELESS SECTION, 3 MARCH, 1926.

Major B. Binyon, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 3rd February, 1926, were taken as read and were confirmed and signed.

A paper by Mr. R. A. Watson Watt, B.Sc.(Eng.), Associate Member, entitled "The Directional Recording of Atmospherics" (see page 596), and a paper by Messrs. R. A. Watson Watt, B.Sc.(Eng.), and J. F. Herd, Associate Members, entitled "An Instantaneous Direct-Reading Radiogoniometer" (see page 611), were read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 8 p.m.

740TH ORDINARY MEETING, 4 MARCH, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 18th February, 1926, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 401) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Mr. R. Borlase Matthews, Member, entitled "Electro-Farming, or the Application of Electricity to Agriculture" (see page 801), was read and discussed.

On the motion of the President a vote of thanks to the author was carried with acclamation, and the discussion was adjourned at 8.15 p.m. until Thursday, 11th March, 1926.

741ST ORDINARY MEETING, 11 MARCH, 1926.

Lieut.-Col. K. Edgcumbe, R.E. (T.A.), Vice-President, took the chair at 6 p.m., in the absence of Mr. R. A. Chattock, President.

The minutes of the Ordinary Meeting held on the 4th March, 1926, were taken as read and were confirmed and signed.

The discussion on Mr. Borlase Matthews's paper, entitled "Electro-Farming, or the Application of Electricity to Agriculture" (see page 801), was continued.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

742ND ORDINARY MEETING, 18 MARCH, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 11th March, 1926, were taken as read and were confirmed and signed.

Messrs. A. H. Allen and E. W. Dickinson were appointed scrutineers of the ballot for the election and transfer of members and, at the close of the meeting, the result of the ballot was declared as follows :

ELECTIONS.

Associate Members.

Boothby, Thomas Edward.
Lawton, Frederick William.
Maxim, James Leonard, M.Sc.
Reid, Meredith William.
Thompson, Mark, M.A.
Turner, Reginald Alfred.
Wheeler, William.

Graduates.

Aldridge, Percy Spencer.
Aspin, John.
Bryden, James Emmanuel Z., B.Sc.(Eng.).
Burns, John.
Cheney, Cuthbert Samuel G.
Espitalier, Theodore.
Flemons, Sidney.
Goodyear, Sydney.
Haddock, Ralph Burdon.
Harris, Charles Hardie.
Johnston, Eric Montague.
Leeds, Robert James.
Lloyd, Harold.
Lloyd, Norman.
Minowa, Nobuyoshi.
Nakashima, Tomomasa.
Pratt, Joseph Hewitt.
Randhawa, Tara Singh.
Roddis, Charles Henry.
Sutton, Charles Frank, B.A.
Swettenham, Norman Alexander M., B.A.
Tayler, Frederick William.
Wood, William Robert B.

Students.

Arnold, Frederick William.
Arnott, John Thomson.
Ashbrook, Cecil Scott.
Barnes, Leonard Learmouth, B.Sc.(Eng.).
Birch, Stanley Harold.
Bowden, Arthur Ernest.
Brooke, Hugh Allan.
Castling, Norman Voase.
Cluett, Denis Guy.
Cocker, Frederick.
Curtis, Herbert Crichton.
Cuttler, Norman.
Dinenage, Stanley Charles.
Everest, Guy Neil.
Foot, John Bartram L.
Gemmell, William John A., B.Sc.
Jambunadhan, Palamanary Subramanian.
Manser, Harold Walter.
Moolgaokar, Sumantrao.
Morris, Benjamin James.
Phillips, William Austin G.
Pickard, Herbert.
Ramsay, Magnus William.
Ravenscroft, Greville Sanford.
Skipsey, Joseph Fendley.
Smith, George.
Teasdel, Carrick Jex.
Thomas, Edward Arthur.
Thomson, George Francis.
Trippier, Harry Alfred.
Ward, Alfred Arthur.
Whetter, William Arthur.
Williams, Charles Harry.
Wilson, Neville.

Associate.

Napier-Whittingham, Duncan.

TRANSFERS.

Associate Member to Member.

Hefford, Charles Nelson, M.Sc.
Horne, Walter Frederick M.
McDouall, Alan Patrick.
Mann, Frank Harris.
Plevin, Percy Johnson.
Randall, Oswald Raymond, Ph.D., M.Sc.
Scott, William Robert.
Wimalasurendra, Devapoora Jayasena.

Graduate to Associate Member.

Ashley, William Herbert.
Cluley, Gordon.
Farmer, Claude Douglas.
Finlay, James.
Gibson, Francis Barker.
McCulloch, Reginald Andrew.
Whittenham, Albert John L.

Student to Associate Member.

Currah, Launcelot Edgar.
Fearon, Philip Vivian, B.Sc.(Eng.).
Filmer, Charles.
Harris, Henry Cecil.
Housden, Frank Robert, B.Sc.(Eng.).
Neal, Albert Frederick, B.Sc.(Eng.).
Thirtle, Arthur Charles.
Thomson, Douglas Charles, B.Sc.

Student to Graduate.

Andrewes, Humfrey, B.Sc.
Batt, Frederick Horace.
Cooper, Harold Ritter.
Davies, Evan Daniel, B.Sc.
de Aguiar, Joas.
Forster, William Johnston.
Foulkes-Roberts, David Swynford, B.Sc.(Eng.).
Hawkings, Reginald John, B.Sc.(Eng.).
Loureiro, Thomaz Edson.
MacElwee, Norman MacLeod, B.Sc.
McWhirter, Harry Roy S., B.Sc.(Eng.).
Mavor, Albert Bernard.
Obert, Ferdinand Thomas F.
Roach, John Carlyle, B.E.
Scott, Frank Calder.
Stephenson, Eric Fletcher, B.Sc.(Eng.).
Stretch, William, Jun.
Tamplin, Struan Robertson.
Thornton, Edward Charles B.
Tuson, Kenneth Hadley.
Ward, John Wilfred, B.Sc.(Eng.).
Watkinson, Joseph Edwin.
Wilkinson, Leslie.
Williams, Alec Duncan.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. L. C. Grant, Associate Member, entitled "Developments in High-Power Fusible Cut-Outs," was read and discussed.

On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.45 p.m.

INSTITUTION NOTES.

Council for the Year 1926-27.

The scrutineers (Messrs. P. M. Baker, A. Murray Coombs and A. F. Harmer) appointed at the Ordinary Meeting held on the 22nd April, 1926, in connection with the ballot to fill the vacancies which will occur in the Council on the 30th September next, have reported to the President that 1 420 ballot papers were returned, of which 20 were spoiled, and that the result of the ballot is as follows :—

President : Dr. W. H. Eccles, F.R.S.

Vice-President : Colonel T. F. Purves, O.B.E.

Hon. Treasurer : Lieut.-Col. F. A. Cortez Leigh, T.D., R.E.

Ordinary Members of Council : (Members) Mr. A. C. Cramb, Dr. A. H. Railing, Dr. S. Parker Smith, and Mr. A. J. Stubbs ; (Associate Member) Mr. F. W. Crawter.

The Council for the year 1926–27 will therefore be constituted as follows :—

President.

W. H. Eccles, D.Sc., F.R.S.

The Past-Presidents.

A. Siemens.
Col. R. E. Crompton, C.B.
J. Swinburne, F.R.S.
Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S.
W. M. Mordey.
S. Z. de Ferranti, D.Sc.
Sir John Snell, G.B.E.
C. P. Sparks, C.B.E.
R. T. Smith.
Ll. B. Atkinson.
J. S. Highfield.
F. Gill, O.B.E.
A. Russell, M.A., D.Sc., LL.D., F.R.S.
W. B. Woodhouse.
R. A. Chattock.

Vice-Presidents.

Lieut.-Col. K. Edgcumbe, R.E. (T.A.).
A. Page.
Col. T. F. Purves, O.B.E.
Prof. W. M. Thornton, O.B.E., D.Sc.

Honorary Treasurer.

Lieut.-Col. F. A. Cortez Leigh, T.D., R.E.

Ordinary Members of Council.

A. C. Cramb.
F. W. Crawter.
The Viscount Falmouth.
Prof. C. L. Fortescue, O.B.E., M.A.
R. Grierson.
Major E. O. Henrici, R.E. (Ret.).
W. E. Highfield.
H. Jones.
E. Leete.
Sir B. Longbottom.
R. W. Paul.
A. H. Railing, D.Eng.
C. Rodgers, O.B.E., B.Sc., B.Eng.
E. H. Shaughnessy, O.B.E.
S. Parker Smith, D.Sc.
A. J. Stubbs.
J. W. T. Walsh, M.A., M.Sc.
S. J. Watson.

And

the Chairman and Immediate Past-Chairman of each Local Centre.

Associate Membership Examination.

The Council have revised and extended the list of qualifications which exempt from the Associate Membership Examination. Full particulars relating to such exemptions can be obtained from the Secretary.

National Certificates and Diplomas in Electrical Engineering.

The following have been approved under the scheme drawn up by the Board of Education and the Institution :—

Approved for Ordinary Grade Certificates (Senior Part-time Course) :—

Barnsley Technical School.

Approved for Higher Grade Certificates (Advanced Part-time Course) :—

Stafford County Technical School.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 June–25 July, 1926.

	£	s.	d.
Adcock, F. W. D. (Rickmansworth) ..		5	0
"Anonymous"		5	0
Barton, E. G. C. (Vevey, Switzerland) ..	1	0	0
Berindei, M. (London)		10	6
Crocker, E. (Birmingham)		5	0*
Duncan, W. (Edinburgh)		10	6
Farrant, J. A. P. (Southampton)		5	0
Fox, H. C. (Birmingham)		5	0*
Grainge, J. R. W. (London)		5	0
Green, F. W. (Melbourne)		5	0
Greig, J. (Montreal)		8	0
Hawkins, R. C. (London)		5	0
Jago, E. H. (Wallasey)		10	0
Jones, W. E. (Sutton, Surrey)		15	0
Kerr, W. W. (Newton Mearns, N.B.) ..		5	0
Leigh, J. H. (Manchester)		5	0
Lisle, G. S. (Gateshead)		5	0
McKellar, D. J. (Glasgow)		10	0
Manning, J. W. G. (Barking)		8	0
Mortimer, S. (Penang)		10	0
Mounsdon, C. F. (Sevenoaks)		2	6
Pausey, E. B. (Wallasey)		5	0
Plowman, R. C. (Rugby)		5	0
Redman, W. (Shipley)		5	0
Reeman, H. F. (Manchester)		5	0*
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ELECTRIFICATION OF A SECTION OF THE ORLÉANS RAILWAY.

By H. Parodi.

(*Paper received 4th January, 1926; read at a Joint Meeting of* The Institution *and the British Section of the French Society of Civil Engineers 18th February, also before the* South Midland Centre *17th February, and before the* North Midland Centre *23rd February, 1926.*)

Summary.

The author first discusses the conditions which have led the French Government to consider an extensive electrification scheme, of which the railways will form only a part, and he then explains the general method adopted in drawing up the scheme and utilizing in the most economical manner the sources of power available.

Particulars are given of the power supply to the Orléans Railway and the rolling stock already in use and on order.

Finally, the design of electric locomotives is discussed, and a comparison is made between electric and steam locomotives.

Introduction.

This paper is not intended to describe in detail the important electrification scheme now being carried out by the Orléans Railway Company, but merely to outline those features which will show how it fits into the general electrification programme of France.

At the present time, when Great Britain would appear to be on the eve of extensive electrification work, which will doubtless be carried to a successful conclusion in view of the exceptional skill of British engineers and the determination of the Government, the author thinks that it may be of interest to describe the schemes proposed for France and the methods which are being employed. In this connection British engineers will probably be more interested in the reasons for the selection of particular methods than in the actual methods themselves, because valuable information obtained by experience in any large undertaking cannot be profitably made use of unless the real aims of those responsible for the work, together with any conditions which may have been laid down or which may have arisen during the progress of the work, are thoroughly understood.

It will be obvious that so vast a programme of electrification as that projected in France cannot be carried out immediately, especially when it is remembered that many big undertakings have required the efforts of several generations before being brought to a successful conclusion. If, however, the general plan is outlined and the principles underlying its organization and the methods adopted for carrying it out are clearly explained, it will be realized that the work—the completion of which has been retarded by the present financial stringency—will be taken up again with a new zeal as soon as circumstances permit, because its realization constitutes, for a country like France, one of the most efficient means of re-establishing stable conditions.

It is for this reason that, in the first part of the paper, the author has outlined the main factors which have dominated the whole of the investigation regarding the scheme of electrification in France and the development and economical use of water power. The second part of the paper is devoted to a brief description of the electrical equipment installed, or being installed, by the Orléans Company.

The author would have liked to explain the technical considerations which influenced the choice of those sections of railway to be electrified first, and also to describe the principles and methods which have been applied in the design and construction of the high-tension transmission lines, substations, transformer stations, and distribution lines. It is, however, impossible for him to go into all these questions now, and he therefore proposes merely to include in an Appendix a few remarks on the layout of the electric locomotive rolling-stock. Those who are interested in these questions will, however, find a detailed description of the electrification of the Orléans Railway system in a paper which the author has written for publication by the *Revue Générale des Chemins de Fer.*

Part 1.

Scheme of Electric Power Supply and Railway Electrification in France.

The electrification of the Orléans Railway is of particular interest, not only on account of the importance of the scheme, but also owing to the magnitude of the problems arising in carrying out the work. It was a question not merely of substituting electric traction for steam traction on a line having a dense traffic, but also of providing a large distribution system of which the power plants and transmission lines could be utilized for a supply of electric power in all the districts through which the railway passes.

The policy adopted in France in connection with the electrification of the railways is substantially different from that followed in other countries. The substitution of electric power for steam on the railways is considered in France to be one stage of a more comprehensive scheme, whereas in Germany, Switzerland, Austria, Sweden, Norway and other countries, the electrification of the railways is considered independently of the problem of a general supply of electric power. The railways in all the countries mentioned belong to the State, and special power stations and transmission lines have been installed for the generation and utilization of single-phase current at a low frequency. Two entirely separate and independent systems are thus being developed side by side, the power supply to the industrial system being by three-phase current at 50 periods, and the State power-supply system for electric traction being single-phase current at a frequency of $16\frac{2}{3}$ periods. The only indication of a desire to

establish at a later date an electrical connection between the traction and industrial systems, with a view to an exchange of power between them, is that the ratio between the frequencies of the two systems is a whole number, namely $50 \div 16\frac{2}{3}$, i.e. 3.

In Great Britain, France, Belgium, Holland, Spain, Africa (Morocco, Algeria and Natal), as well as in South America (Chili, Argentine, etc.) electric power for traction will be generated and transmitted as three-phase current at 50 periods (60 periods in South America).

All the countries which have followed the policy of interconnecting the traction and industrial power systems have adopted high-tension direct current at 1 500 to 4 000 volts as their standard for traction. Such current can, of course, be obtained whatever the frequency of the current generated. It should, however, be pointed out that in certain countries, such as Italy and Hungary, very interesting tests are at present being made with a view to using for single-phase or three-phase traction three-phase current of a frequency such as is employed for the industrial supply. In Italy three-phase locomotives having gears and connecting-rods and using current at the industrial frequency have been tested on the Mont Cenis lines; and single-phase and three-phase 50-period locomotives fitted with synchronous converters on De Kando's system are under test in Hungary on a suburban line near Budapest.

This development, which is taking place in countries where low-frequency alternating-current traction has been in operation for a long time, proves more conclusively than any theoretical considerations the practical advantages to be obtained by standardizing the various systems adopted for the generation and transmission of electric power.

As the main flow of traffic always follows in every country the same direction whatever the form of transport, it would seem that the general direction of the main power-transmission lines should practically coincide with that of the railway lines which have a very dense traffic, and such railway lines are, as a matter of fact, those where the question of electrification is of most interest. For instance, the railway from Paris to Toulouse through Orléans, Limoges and Brive, is the route of the power-transmission line which would allow of an exchange of power between the large steam-driven power stations of the Paris district and the hydro-electric stations of the Central Plateau and the Pyrenees.

Considered from this aspect, the electrification of the railways no longer appears merely as an " end " but also as a "means." It will therefore be understood why eth French Government had, even before the war, brought pressure to bear upon the large railway companies supplying districts rich in water power to electrify their systems so as to prepare the way for a still more extensive electrification.

The total coal consumption in France now reaches about 70 million tonnes* per year, 75 per cent of which is obtained from the country's mines and 25 per cent from English, Belgian and German mines. The whole of the French railways do not consume more than 9 million tonnes, i.e. about 13 per cent of the total. From this it can be seen that the electrification of the railways, even if extended to include every line, would result in only a small reduction in the import of fuel into France.

In order to obtain an appreciable reduction in the amount of coal purchased abroad, which forms a serious item in the trade balance, it is necessary to transmit electrical energy obtained from water power to large cities like Paris, Lyons, Bordeaux and Toulouse, where the coal bill in connection with the generation of the electrical energy required for industry, namely motive power and lighting, is far bigger than that for traction purposes.

Fig. 1 clearly shows this condition. On each railway line where the electrification is complete or nearly complete, a rectangle has been drawn having its area proportional to the annual consumption of coal for traction on railways. In this connection it should be remembered that the traffic figures for 1913 are now exceeded on all the railways.

A circle has been drawn round Paris and its area represents to the same scale the fuel consumption in the steam-driven power plants of the Paris district which supply the industrial requirements for electric power and lighting. The amount of coal thus consumed in Paris (1 200 000 tonnes in 1924) is more than three times greater than the coal consumption for steam haulage of all the trains of the Orléans Company between Paris and Brive.

By the end of 1935 the consumption of electrical energy in Paris will reach 2 000 million kWh, whereas the requirements for electric traction on the Orléans system (the lines from Paris to Brive, from Saint Sulpice to Gannat, and from Brive to Clermont) will very probably not be higher than 400 million kWh. The maximum demand in Paris will be about 1 million kW, whereas the traction demand will not exceed 80 000 kW.

The whole problem of the electrification of the Orléans Railway has been dominated by the desire to transmit electrical power from the Central Plateau to Paris without burdening the railway electrification with capital charges which are out of proportion to the present traction requirements. The solution of this problem has been found in the systematic use of transmission lines at as high a voltage as possible.

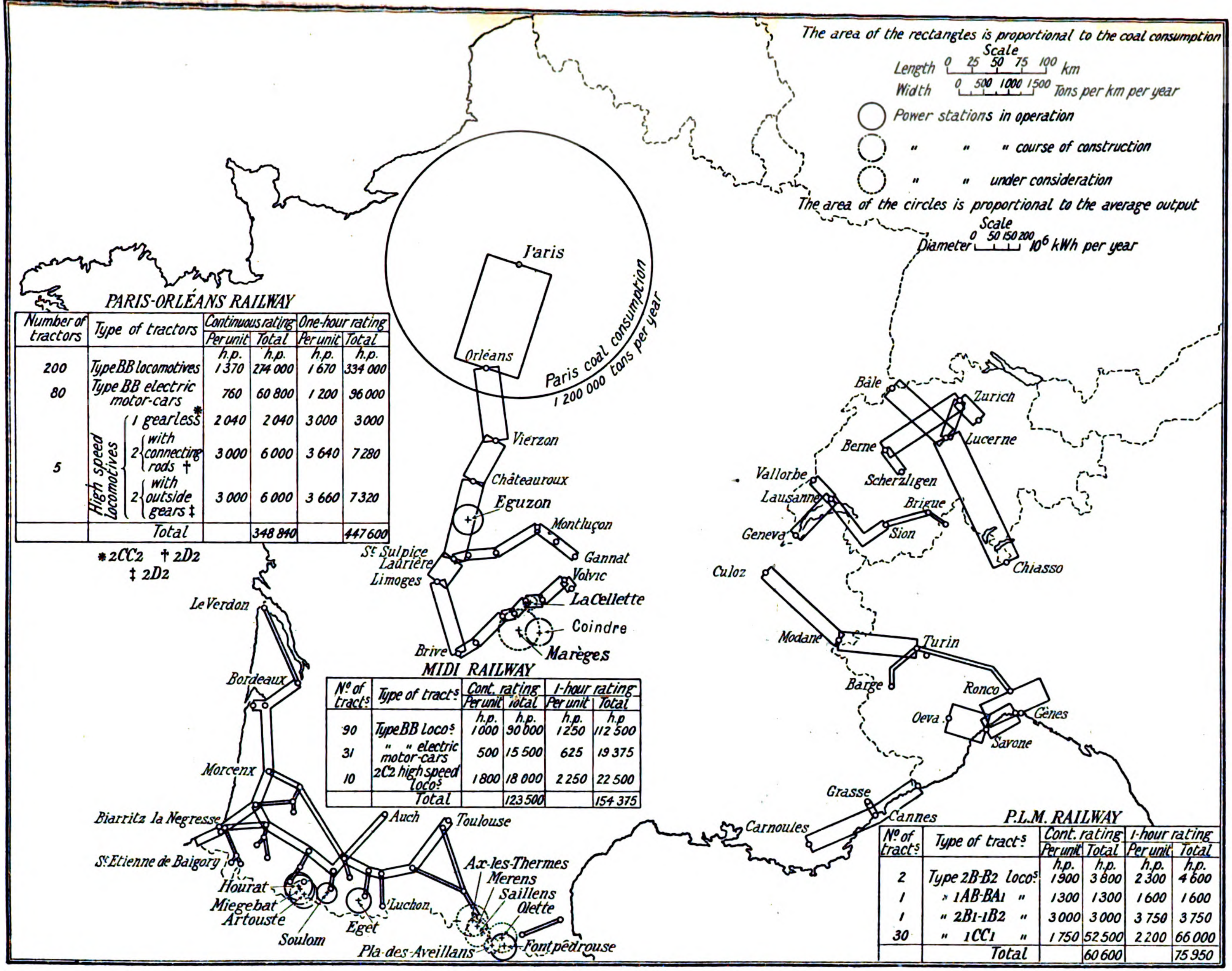
Power Transmission System.

The use of very high voltages presents considerable advantages from an electrical point of view, particularly in connection with the great strength of such lines and their almost complete immunity from atmospheric phenomena. Economically the advantages are not less important, and they become more evident when, bearing in mind that the amount of power which can be transmitted to a given distance varies as the square of the voltage, it is found that the first cost increases practically only as the voltage.

Owing to the increase in the transmission voltage, a saving is certain to result if we transmit over the same line a long-hour load such as traction (say 4 000 to 5 000 hours per annum) and a shorter-hour industrial load (2 000 to 2 500 hours per annum).

From experience on distribution systems in France, it is found that the cost of a transmission line can be

* Wherever "tonne" is mentioned in this paper, "metric ton" (1000 kg) is meant.



PARIS-ORLÉANS RAILWAY

Number of tractors	Type of tractors	Continuous rating Per unit	Continuous rating Total	One-hour rating Per unit	One-hour rating Total
		h.p.	h.p.	h.p.	h.p.
200	Type BB locomotives	1 370	274 000	1 670	334 000
80	Type BB electric motor-cars	760	60 800	1 200	96 000
5	High speed locomotives: 1 gearless*	2 040	2 040	3 000	3 000
	2 with connecting rods †	3 000	6 000	3 640	7 280
	2 with outside gears ‡	3 000	6 000	3 660	7 320
	Total		348 840		447 600

* 2CC2 † 2D2
‡ 2D2

MIDI RAILWAY

Nº of tract^s	Type of tract^s	Cont. rating Per unit	Cont. rating Total	1-hour rating Per unit	1-hour rating Total
		h.p.	h.p.	h.p.	h.p.
90	Type BB Loco^s	1 000	90 000	1 250	112 500
31	" " electric motor-cars	500	15 500	625	19 375
10	2C2 high speed loco^s	1 800	18 000	2 250	22 500
	Total		123 500		154 375

P.L.M. RAILWAY

Nº of tract^s	Type of tract^s	Cont. rating Per unit	Cont. rating Total	1-hour rating Per unit	1-hour rating Total
		h.p.	h.p.	h.p.	h.p.
2	Type 2B-B2 loco^s	1 900	3 800	2 300	4 600
1	" 1AB-BA1 "	1 300	1 300	1 600	1 600
1	" 2B1-1B2 "	3 000	3 000	3 750	3 750
30	" 1CC1 "	1 750	52 500	2 200	66 000
	Total		60 600		75 950

FIG. 1.—Map showing for the year 1913 the coal consumption per kilometre per annum on the electrified lines.

represented approximately by an expression of the form

$$a + bE$$

where E is the transmission voltage.

The minimum return which must be obtained each year in order to cover the capital charges and the working expenses should also be of the form

$$a + bE$$

If N be the number of hours during which an amount of power kE^2 is transmitted or can be transmitted along the line, the amount of energy transmitted yearly will be kE^2N.

If p be the average receipts per unit transmitted, in order that the revenue and expenditure may balance we must therefore have

$$kE^2Np = a + bE \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If, now, in order to allow loads of various types to be superimposed, we increase the voltage without altering the tariff p, we get by differentiating equation (1)

$$kp(E^2dN + 2ENdE) = bdE$$

Therefore

$$\frac{dN}{dE} = \frac{b - 2kpEN}{kpE^2} = -\frac{pkEN + a/E}{kpE^2} \quad . \quad . \quad (2)$$

Whatever the values of the constants, the quantity dN/dE is thus negative, which means that any increase in the voltage will enable a reduction in the minimum time of utilization necessary in order to be able to transmit power at a given price.

With the voltage of 150 kV now used, it is possible to transmit economically 40 000 to 50 000 kW from the Central Plateau to Paris, a distance of about 450 km (280 miles). By increasing the voltage to 220 kV, however, it would be possible to double (i.e. $220^2/150^2$) the amount of power transmitted, and to superimpose on a traction load of 30 000 to 40 000 kW a power load of 60 000 or 70 000 kW, which could be used for industrial power and lighting.

The high-tension system of the Orléans Company now includes a 150-kV line which can later be converted for use at 220 kV by the addition of a few units and a shield to the present chain insulators. The sizes of the aluminium conductors with their steel cores (293 mm^2 total section), and also the dimensions of the towers, have been based on the ultimate adoption of a voltage of 220 kV. In fact, the normal distance between conductors (about 7·80 m, or 25 ft. 6 in.), and that between conductors and the main support (about 3 m, or 10 ft.) are larger than those actually employed on the 220-kV lines in operation in California.

Correct Method of Generation and Utilization of the Power Obtained from Waterfalls.

In countries like Great Britain where electric power can be obtained only by burning coal, and in countries possessing waterfalls fed from water sources all of the same type, as in Switzerland, the problem of the generation of electricity is almost exclusively a technical one, particularly when, as is the case in both the countries mentioned, the coal resources in one and the water-power resources in the other are very much larger than the national requirements.

The problem becomes, however, much more complicated in countries like France where important coal resources and considerable water power are both available at the same time, although the amount of water power varies throughout the year. The coal resources of France are estimated at 22 000 million tonnes, taking into consideration only those deposits which can be worked with the appliances at present available. With the present output of 40 to 60 million tonnes per annum, coal will thus be available in France for between 400 and 500 years. The water-power resources, which are renewed every year by solar heat, are estimated to represent normally about 5 million kW, of which about 3·3 million kW is in the form of waterfalls fed by glaciers, and 1·7 million kW is in waterfalls depending for their water supply on rain. Of this total, only 0·67 million kW was being utilized on the 1st January, 1925, whilst 0·28 million kW was in course of development at the same date.

The present consumption of electric power in France is about 7 500 million kWh, of which about 4 500 million kWh is generated by steam plants, the output of which represents 2 000 hours' use per annum, and 3 000 million kWh is obtained from water power, representing 4 300 hours' use. The combined load of the interconnected electric distributing systems represents about 2 500 hours' use per annum, i.e. a load factor of about 28 per cent.

The Government is considering at the present time in France, in close co-operation with manufacturers, a programme of gradual equipment and of progressive linking-up of the various distribution systems, rather than Government control of electricity generation. The problem is too important, from the point of view of the country as a whole, for the Government not to try to outline the method of generation to be followed; and it is also too complicated, owing to the various opposing interests, to admit of the laying down of a hard-and-fast technical solution.

From the point of view of the rapid utilization of the waterfalls, decentralized efforts are perhaps desirable; but as regards the operation of the plant and its efficiency, unity of control is essential. Let us therefore try first to state the conditions of the problem from the purely technical point of view, and then to discuss how the action of the railway companies would seem to facilitate the carrying out of a comprehensive electric power scheme on correct lines.

The power $F(t)$ available at each instant in a complex system consists of four terms, each a function of the time. Thus

$$F(t) = \Sigma H(t) + \Sigma R(t) + \Sigma S(t) + \Sigma T(t)$$

where $\Sigma H(t)$ represents the total power available from stations using streams and rivers where there are no reservoirs or where the reservoirs are full;

$\Sigma R(t)$ represents the total power available from power stations having daily or weekly reservoirs;

$\Sigma S(t)$ represents the total power available from power stations with seasonal reservoirs;

and $\Sigma T(t)$ represents the total power available from steam-driven stations.

In the case of a complex power system the problem to be solved, first as regards the layout and then as regards the operation of the system, consists in proportioning those items which are more or less completely disposed of at the commencement of the scheme; that is to say, of so equipping the power stations referred to as H, R, S, and T above, and determining the capacity of the reservoirs in connection with stations R and S, as to allow of dealing with the fluctuations of load $\phi(t)$ with the smallest expenditure of fuel.

Power stations without reservoirs (H above) are essentially those the output of which must not be controlled. Power stations R are the peak plants or "system regulators"; and power stations S and T are the additional ones substituted for H and R during periods of drought.

The available power $S(t)$ of a system should include any power $H'(t)$ taken from a neighbouring system if the plant H' is driven by a water supply of a type different from that used by the plant H of the first system.

If the load $\phi(t)$ is solely traction, it will be found that the monthly or, even, weekly power demand is practically the same throughout the year. Whereas if the load $\phi(t)$ is an industrial one for power and lighting, in addition to large daily variations there will also be seasonal variations, the maximum power demand occurring during the winter and the minimum during the summer.

Whatever the nature of the consuming system, the load curve for $\phi(t)$ is characterized by two "factors" corresponding to the normal periods of variation of the load. The load curve can therefore be considered to be practically a double function of the time. To each period of 24 hours corresponds a portion of curve of almost constant shape, which is repeated daily with but slight variation.

Supposing now that from the load curve $\phi(t)$ we obtain a second curve representing the variation in the total amount of electrical energy generated during each period of 24 hours throughout the year, and let us represent by e the amount of energy generated during the day having the greatest output. If we call E the total amount of electrical energy generated during the year and P the maximum demand, we shall be able to define three load factors:—

The normal load factor

$$f = \frac{E}{365 \times 24P}100$$

The daily utilization factor of the maximum demand P

$$\lambda = \frac{e}{24P}100$$

And the yearly utilization factor of the maximum daily output

$$\mu = \frac{E}{365e}100$$

The normal load factor is equal to the product of the two others divided by 100.

That is

$$100f = \lambda\mu$$

If, instead of defining the factors λ and μ in distinguishing in the load curve of a system the customary periods, the day and the year, we define similar factors λ' and μ'—the first corresponding to the equivalent hours of use of the maximum demand during the month of heaviest load, and the second to the utilization during the 12 months of the year of the maximum monthly demand—we shall have facilitated somewhat a solution, as it will then be comparatively easy to compare the curve $F(t)$, defining the available power, with the curve $\phi(t)$ representing the demand.

The equipment of water-power stations possessing

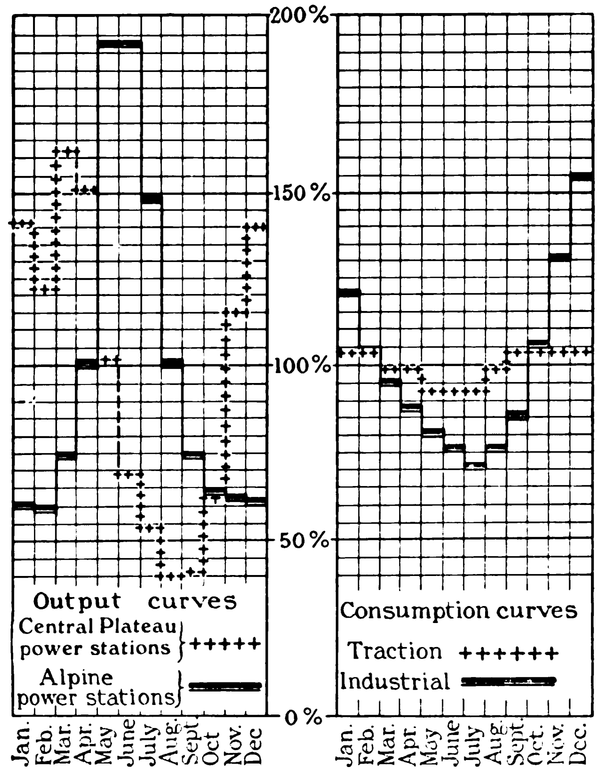


FIG. 2.—Curves showing output of the Central Plateau and Alpine power stations, and the energy consumption for traction and industrial purposes.

daily or weekly reservoirs $R(t)$ should be such that they can develop, with the help of plants $H(t)$, an output as nearly as possible that defined by the utilization coefficient λ'.

Water-power stations possessing seasonal reservoirs $S(t)$ should be equipped in such a manner as to be in a position to give, at times when plants $H(t)$ and $R(t)$ will only be able to operate at reduced load, an output as nearly as possible that defined by the utilization coefficient μ'.

The extra seasonal power will be supplied by the steam-power stations or by water-power stations $H'(t)$ obtaining their water from a source different from that of the plants $H(t)$.

In the case of a traction supply, μ' differs only slightly from 100 per cent, and λ' is about 50 to 60 per cent according to the length of the electrified line. For

industrial purposes μ' is about 75 per cent and λ' about 33 per cent.

Fig. 2 shows the relative variation in the number of units generated and consumed per month, compared with the number generated and consumed per year. The left-hand side of the figure shows the percentage variation in the number of units generated by the flow of water in the case of a plant depending on rain for its supply (Central Plateau stations), and also of a plant where the water comes from glaciers (Alpine stations). The right-hand side gives the monthly variations in load of an electric railway system and of an industrial system supplying power and lighting.

to the working in parallel of the Eguzon plant (50 000 kW installed) and the large steam-power stations of the Paris district, it will be possible to utilize to the fullest extent the power available from the River Creuse.

In the first stage of the electrification of the Orléans system, the Eguzon plant will represent in the system of power stations of the Société l'Union d'Électricité the equivalent of a 50 000-kW set located at a distance of 300 km (186 miles). This set will be started when water power is available from the Creuse, and it will be stopped when there is no water; but the existence of the weekly reservoir will allow, on the other hand, this power to be used any time during the 24 hours when this reserve

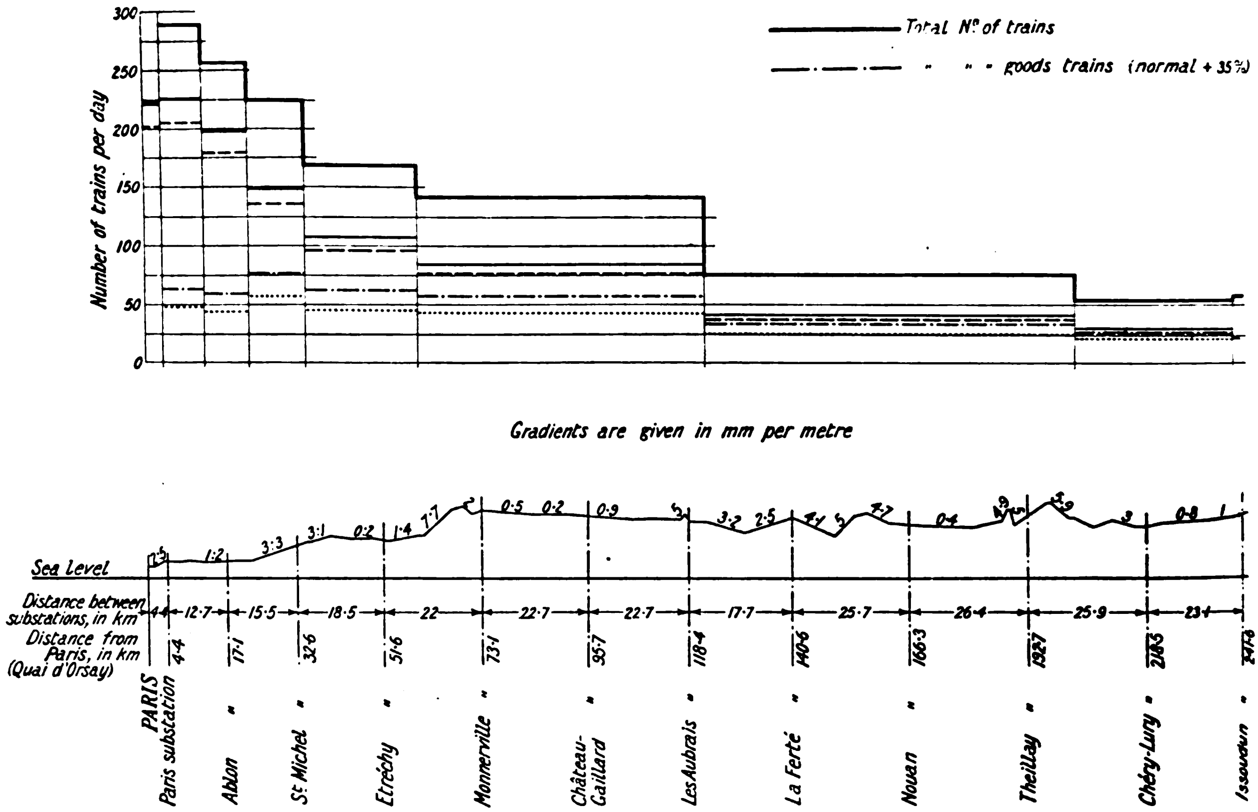


FIG. 3.—Traffic and longitudinal section of the line from Paris to Brive.

As the output curves of water-power plants depending on the rainfall are approximately of the same shape as the consumption curves of industrial systems, we can see at once the advantage which there would be in supplying electric power to Paris from the water power of the Central Plateau, it being particularly easy in this case so to adapt the power available that it will meet the demand.

This was realized by the Government when it authorized the Orléans Company to form, with the help of the Société l'Union d'Électricité, the Société l'Union Hydro-Électrique, in order to install the Eguzon water-power plant on the River Creuse.

The fact that this plant has a dam allows the storage of a sufficient quantity of water to form a weekly reserve, without the possibility of seasonal regulation. Owing

will be most advantageous from the point of view of either economy or reliability.

In the second stage of the electrification of the Orléans system, use will be made of power generated by the hydro-electric plants of the Haute Dordogne. The equipment of the waterfalls will include for the most important power plants the construction up-stream of a reservoir, in order that the adaptation of the available power to the demand may be secured by the use of this reservoir and by the exchange of power with a neighbouring system having water-power plant of a type complementary to the Central Plateau plants.

Owing to this combination and the policy of mutual assistance, the electric traction service of the Orléans Company will be operated under exceptionally reliable

conditions, without the average demand for additional steam power being more than 10 per cent of the total power. Should, in the future, large amounts of hydro-electric power be transmitted from the Central Plateau to Paris, the lines of the Orléans Company could be easily adapted for this transmission.

In superimposing the industrial load on the traction load of the various 90-kV and 220-kV lines, it would be possible to transmit economically 100 000 kW a distance of 450 km (280 miles). The author thought it advisable to emphasize this question of electric power electrify first are the lines having the greatest density of traffic and, consequently, the biggest consumption of coal.

It can easily be shown that the greater the coal consumption per mile of line, the more favourable will be the financial results of electrification. For this reason and others, to which reference will be made later, the Company, after having investigated with the Government the question of commencing the electrification by converting to electric traction the lines in the neighbourhood of the waterfalls of the Central

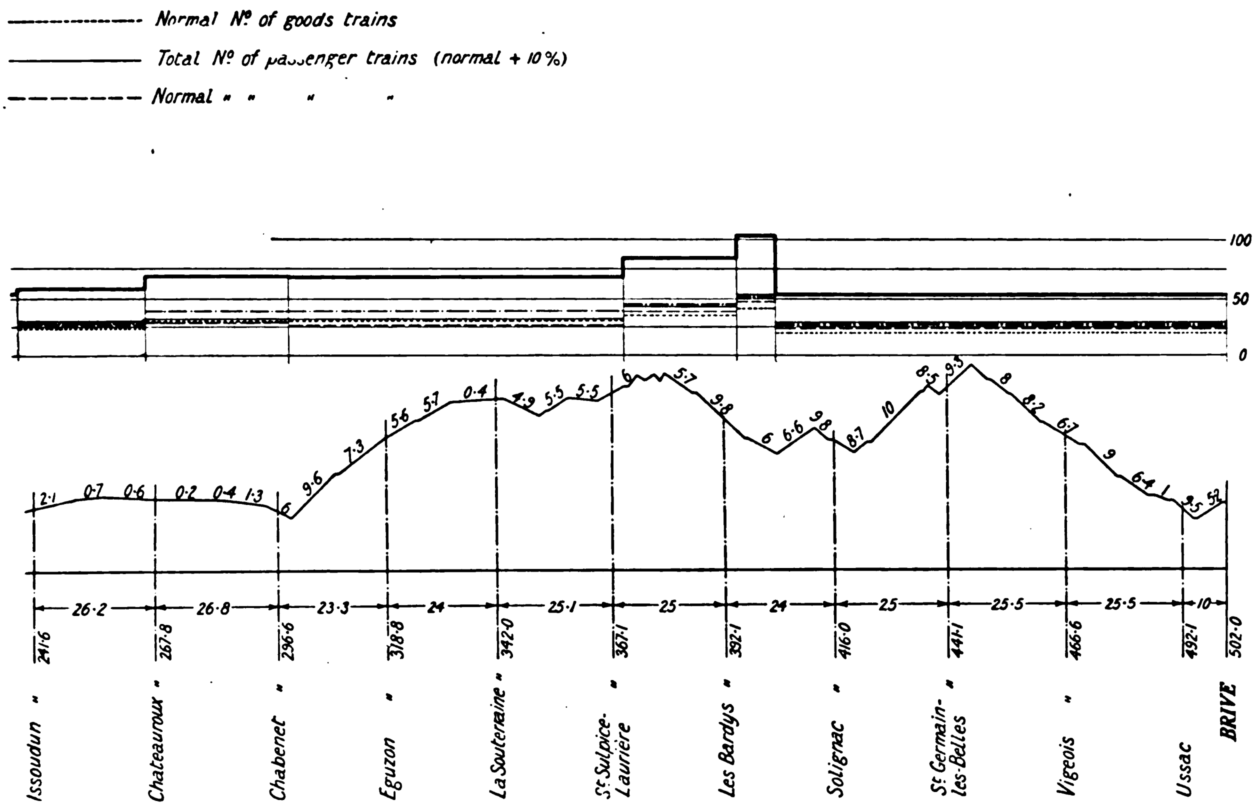


FIG. 3.—*Continued.*

production in a complex system, because on its more or less favourable solution depends the success of the electrification, not only of the railway, but also of the whole country it supplies.

If in a country possessing an abundant supply of coal, such as Great Britain, considerable attention is given to the most economical methods for the generation and distribution of power, it can readily be understood how in France this problem is becoming very important and, we might say, even urgent.

Part 2.

Electric Traction Installation of the Orléans Railway Company.

Of the railway lines from the Central Plateau to Paris, those which the Orléans Company propose to Plateau, eventually decided to carry out the electrification in the following order (see Fig. 1):

Paris to Brive : a length of 502 km (about 312 miles), of which 65 km ($40\frac{1}{2}$ miles) comprises four tracks, and 477 km (297 miles) is double track.

Brétigny to Dourdan : 27 km (about 17 miles) of double track.

Saint-Sulpice to Gannat : 190 km (about 118 miles) of single track.

Brive to Clermont : 198 km (about 123 miles) of single track.

These make a total of 1 576 km (about 980 miles) of main-line track, excluding switching tracks, sidings, and sorting and shunting stations. On these lines

electric traction will replace steam traction for the whole of the passenger, goods, and shunting services.

Figs. 3, 4, 5 and 6 give, for each of the four sections under consideration, a longitudinal section of the line, the distances between the substations, and the number of trains per day.

The scheme has been drawn up with a view to making provision for the following traffic per year :—

40 million tonne-km on the Paris–Orléans section,
20 million tonne-km on the Orléans–Vierzon section,
12 million tonne-km on the Brétigny–Dourdan section,

although, as a matter of fact, the traffic in 1923 only reached 22, 12 and 3½ million tonne-km per kilometre respectively on these sections.

Fig. 7, showing the average yearly traffic on the Paris–Orléans section from 1897 to 1923, clearly indicates the necessity of providing, as has been done, for increased requirements in the future, so as to avoid changing the plant materially during the next 15 years at least.

The orders for the Paris–Vierzon and Brétigny–Dourdan electrification, involving the equipment of over 600 km (370 miles) of main-line track, have all been placed since 1923. Already a number of electric trains are running from Paris (Quai d'Orsay) to Etampes and from Brétigny to Dourdan, a total length of 96 km (59½ miles) of route, and the electric service will be

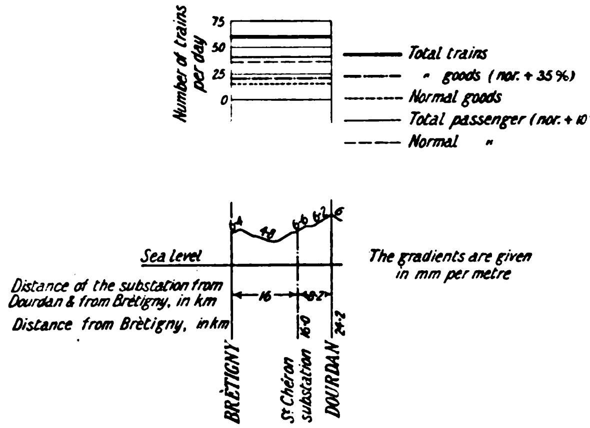


FIG. 4.—Traffic and longitudinal section of the line from Brétigny to Dourdan.

extended as far as Orléans and Vierzon before the end of 1926.

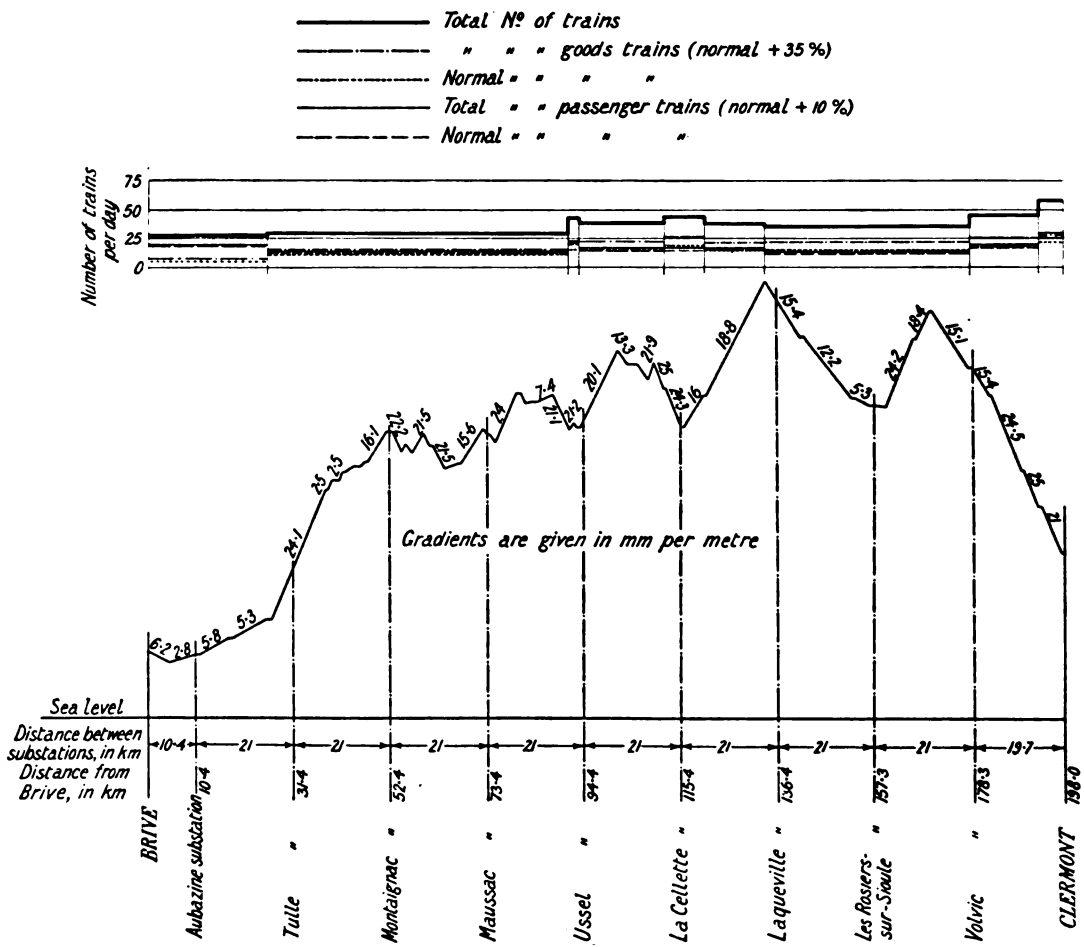


FIG. 5.—Traffic and longitudinal section of the line from Brive to Clermont.

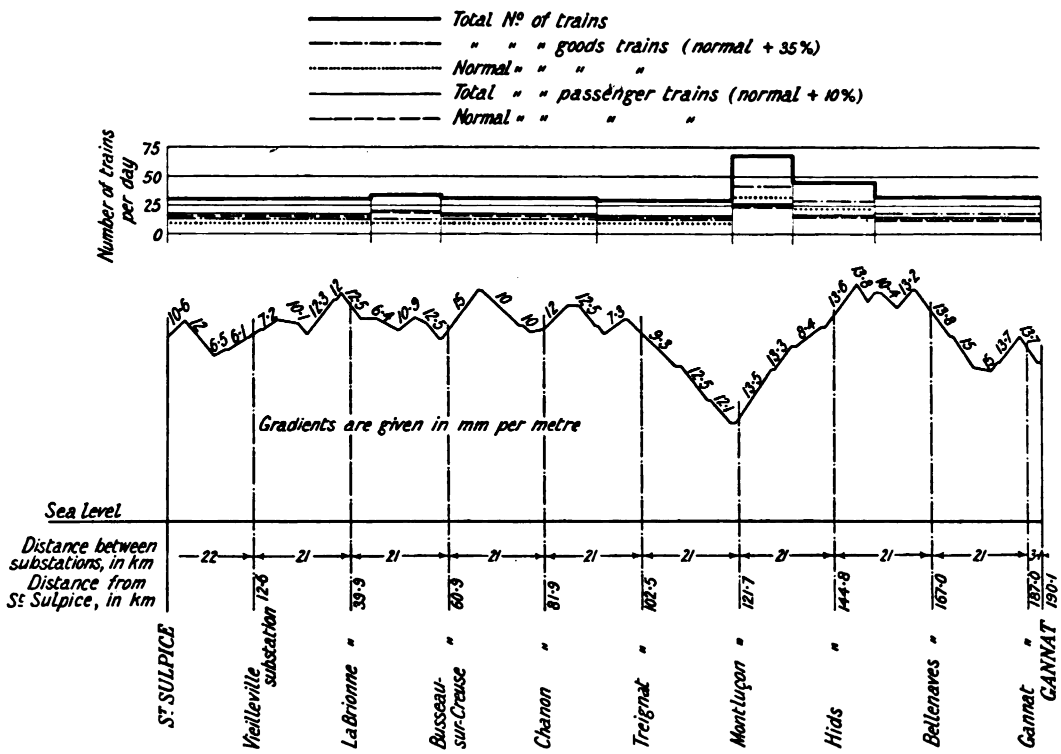


FIG. 6.—Traffic and longitudinal section of the line from St. Sulpice to Gannat.

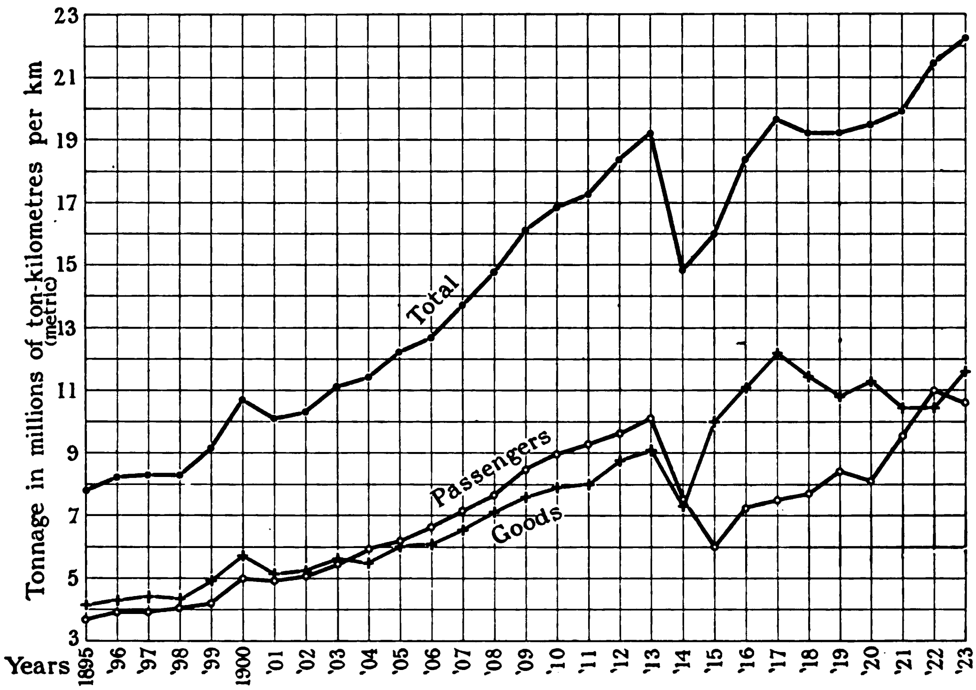


FIG. 7.—Growth of traffic on line from Paris to Orléans.

Electrification of the Paris–Vierzon Section.

Generation of electrical energy.—The electrical energy is generated as three-phase alternating current in a system of power stations comprising at present:—

(1) The steam-power stations of the Paris district, namely the Gennevilliers power station (250 000 kW) * and the Vitry power station (80 000 kW) of the Société l'Union d'Électricité.

(2) The water-power plant of Eguzon on the River Creuse, which has a capacity of 50 000 kW and belongs to the Société l'Union Hydro-Electrique, in which the Orléans Company holds an interest.

(3) A group of water-power stations forming part of the concession granted by the State to the Orléans Company. These stations can supply throughout the year an average demand of 100 000–150 000 kW depending on their equipment. Two plants, those at Coindre (20 000 kW) and Chavanon (25 000 kW) are in course of erection. A third, that at Marèges of 100 000 kW capacity, is under consideration.

The unavoidable fluctuations in the output of the water-power stations will be completely compensated, in the case of the plants on the River Creuse, by the exchange of power between the Eguzon water-power plant and the Gennevilliers steam plant; and in the case of the Haute-Dordogne plant by means of the Chavanon reservoir and by the exchange of power with the Alpine hydro-electric stations. This method, which is rather complicated, is of special interest and reference will be made to it later.

Figs. 8 and 9 (lantern slides), from photographs taken during the course of erection, show the arrangement of the Eguzon and the Coindre plants.

Transmission of power.—The power generated in the various hydro-electric and steam-power stations will be transmitted as follows:—

At 13·5 kV by three three-phase cables, of 150 mm² section per phase, from the busbars of the Vitry steam plants to the Paris and Ablon substations of the Orléans Company.

At 60 kV by three groups of three single-phase cables, of 150 mm² section per phase, the pressure between each phase and earth being 35 kV, from the busbars of the Vitry power station (2 groups of cables) and from Gennevilliers (1 group of cables) to the busbars of the Chevilly substation of the Paris–Orléans Company.

At 90 kV by two three-phase overhead lines, of 238 mm² section (aluminium cable with steel core) and about 300 km (186 miles) in length, from the busbars of the Eguzon power station to those of the Chevilly substation, passing through the 15 traction substations situated along the line from Paris to Eguzon. These lines will be extended to Souillac to feed the seven substations which distribute current for traction between Eguzon and Brive.

* The power indicated in brackets is the capacity of the plant installed.

At 150/220 kV through an overhead line connecting the four transformer substations of Chevilly, Chaingy, Eguzon and Vernéjoux.

At 120 kV through a line connecting the power stations of the Central Plateau to the Alpine stations and following approximately the proposed line under consideration from Commentry to Saint-Germain les Fossés (new section of the Bordeaux–Lyons line).

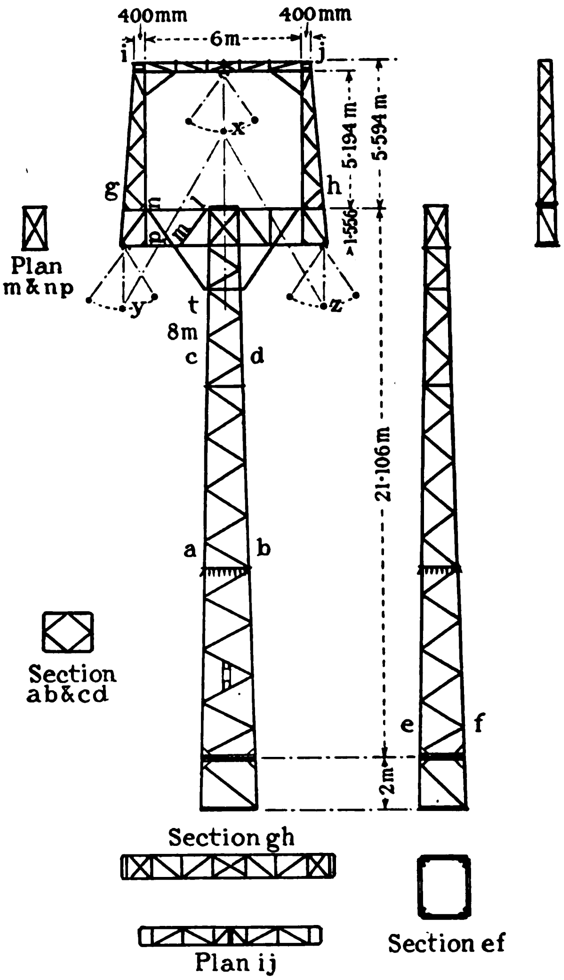


Fig. 10.—Straight-line and 2° angle-type tower for 150–220 kV transmission line.

Span = 250 m.
3 aluminium-steel cables (293 mm).
2 galvanized steel earth wires (60 mm).

Fig. 10 shows the general arrangement of the 90 kV and 150 kV towers, namely, the straight-line towers for 150 kV, the standard towers for 90 kV, and also special towers for the crossing of the River Loire at 90 kV. A view of the lines is given in Fig. 11 (lantern slide).

Transformer substations.—The transmission lines at 60 kV, 90 kV, 120 kV and 150 kV, will be interconnected through five transformer substations situated respectively at Chevilly, Chaingy, Eguzon, Vernéjoux and Commentry. The Chevilly substation connects the 60-kV

system of the Société l'Union d'Électricité to the 90-kV and 150–220-kV systems of the Orléans Company, by means of three banks of static transformers having a total capacity of 75 000 kW, namely: Two banks of 25 000 kW, transforming the current from 60 kV to 90 kV, or vice versa; and one bank of 25 000 kW transforming the current from 60 kV to 150 kV, or vice versa.

This substation is intended to receive later three further lines at 150–220 kV, and eventually two extra lines at 90 kV.

The Chaingy substation is a sectionalizing, transforming and regulating substation. It contains two banks of static transformers, each bank having a capacity of 20 000 kVA. These transformers, of which the two high-tension windings at 150 and 90 kV are star-connected, carry a third winding delta-connected at 6 kV. These 6-kV windings feed the synchronous condensers, each of which is able to supply a maximum reactive power of 10 000 kVA, the current leading or lagging according to the excitation. This substation is intended to receive, in the future, two 90-kV lines which are to be erected in the direction of Tours, and seven extra outgoing feeders at 150–220 kV.

The Eguzon substation connects the Orléans Company's 90-kV and 150-kV systems through the intermediary of the 10 000-volt busbars of the Eguzon power station. The substation contains three banks of transformers totalling 25 000 kVA, namely: Two for transforming from 90 kV to 10 kV; and one for 150 kV to 10 kV.

The plant for the Marèges and Commentry substations has not yet been ordered.

Fig. 12 (lantern slide) shows the general arrangement of the Chevilly substation which has been in operation since October 1924. Fig. 13 (lantern slide) is a view of the 60-kV switches in the Chevilly substation and the incoming underground cables from Gennevilliers.

Rotary transformer substations.—Three-phase current at 50 periods is transformed to direct current at 1 500 volts at 11 substations, representing a total capacity of 54 000 kW for the sections Paris to Vierzon alone (200 km, or 124 miles) and Brétigny to Dourdan (27 km, or about 17 miles). The plant consists of twenty-seven 2 000-kW sets of exactly similar type. Each set comprises two 1 000-kW 750-volt rotary converters connected in series.

Table 1 gives particulars for each substation of the capacity of plant installed and available at peak load.

Fig. 14 (lantern slide) is a view of the static transformers in the Aubrais substation. These comprise three 90 000/555-volt transformers feeding the rotary converters for the traction supply, each of which is rated at 2 000 kW and has a maximum ouput of 6 000 kW, and three 90 000/30 000-volt transformers for supplying the power and lighting requirements of the district.

Fig. 15 (lantern slide) shows a general view of the Etréchy substation in which transformers having a total capacity of 6 000 kW are installed for the traction supply.

Contact conductor.—Direct current at 1 500 volts is distributed along the track by means of compound catenary lines having a double contact wire. The poles are placed on alternate sides of the track and are spaced 64 metres (210 ft.) apart.

The main supporting cable is of phosphor bronze of 116 mm² section. The other cables are of electrolytic copper of the following cross-sections: auxiliary carrier 104 mm²; contact wires 107 mm².

Fig. 16 (lantern slide) is a view of the lines in the 4-track section from Paris to Etampes; whilst Fig. 17 (lantern slide) shows the lines at the entrance to Juvisy station.

On the suburban section from Orsay to Brétigny a third rail,* used also as a feeder, is provided in addition to the overhead line. The shape and method of support of the third rail are shown in Fig. 18. Beyond Brétigny the carrying capacity of the catenary line is increased by means of a copper feeder of 240 mm² section.

TABLE 1.

Substations	Supply voltage	Number of sets proposed	Number of sets installed	Present power available
	kV			kW
Paris	13·5	4	3	12 000
Ablon	13·5	4	3	12 000
Saint-Michel.. ..	90	4	3	12 000
Etréchy	90	4	3	12 000
Monnerville	90	3	2	6 000
Château-Gaillard ..	90	3	2	6 000
Les Aubrais	90	4	3	12 000
La Ferté	90	3	2	6 000
Nouan	90	3	2	6 000
Theillay	90	3	2	6 000
Saint-Chéron ..	90	3	2	6 000
Totals	—	34	27	96 000

ROLLING-STOCK.

The suburban trains consist of motor coaches and trailers, whilst the main-line trains, both passenger and goods, are made up of the ordinary rolling stock hauled by electric locomotives.

Motor coaches.—Each motor-coach multiple-unit train consists of one, two or three power units, each unit comprising an electric motor coach weighing 65 tonnes and two bogie-type trailers each weighing 34 tonnes, the total weight of the train therefore being 133 tonnes. Each motor coach is fitted with two independent bogies, and each bogie carries two 250-h.p. 750-volt motors which are permanently connected in series.

An order has been placed for 80 motor coaches, from which 25 multiple-unit trains of three units each will be formed for the suburban service. At present eight motor coaches are in service, some at 1 500 volts and others temporarily at 600 volts on the old electric traction system.

Locomotives.—Goods and passenger trains rated for

* Experience has shown that this third rail allows current to be collected with certainty even in the winter. Owing to two neighbouring tracks being provided with third rails having the ordinary type of surface contact, it has been possible to make definite comparisons, with the above-mentioned result.

speeds lower than 75 km per hour are hauled by double locomotives comprising two units. Each unit, or half-locomotive, is supported on two bogies, and each bogie carries two 1 500-volt motors with forced ventilation. Each motor has, depending on the type, a one-hour rating of from 375 to 430 h.p. and a continuous rating of from 300 to 375 h.p. The unit is designated by the symbol " BB + BB."

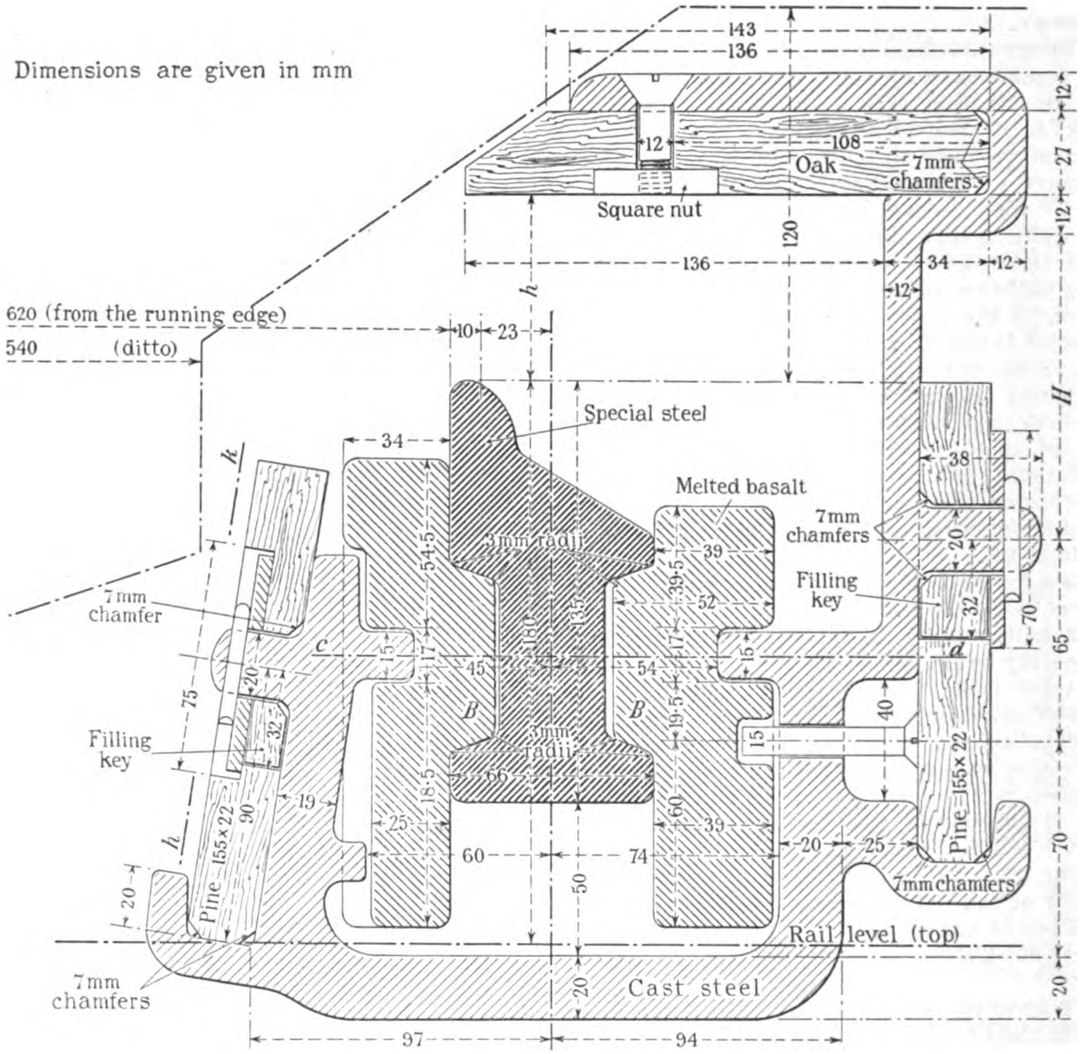


FIG. 18.—Contact rail.

200 half-locomotives have been ordered, and more than 50 of these have been delivered and are under test or in operation on the electrified lines.

Express trains, that is trains having a nominal speed higher than 65 or 70 km per hour, are hauled by special locomotives of slightly greater power than the double goods locomotives, but of lighter construction and specially designed for attaining high speeds.

Five experimental locomotives have been ordered, three of which have been delivered and are under test and adjustment. One is a gearless locomotive of the type " 2C + C2," having a one-hour rating of 2 700 h.p. and capable of developing 2 100 h.p. continuously. Two of the locomotives are of the type " 2D2 " with connecting-rod drive, and have a one-hour rating of 4 000 h.p. and a continuous rating of 3 500 h.p. One of these is fitted with " hyperstatic " connecting-rods and motors of the usual type, whilst the other has " isostatic " connecting-rods, flexible couplings and fully compensated motors. The other two locomotives are of the type " 2D2 " with outside gear-drive and small connecting-rods, and have a one-hour rating of 3 600 h.p. and a continuous rating of 3 000 h.p. One of these locomotives is provided with standard running gear and motors, and the other with adjustable articulated running gear and fully compensated motors arranged for regeneration.

Figs. 19, 20 and 21 (lantern slides) show a gearless locomotive, a locomotive with connecting-rods, and a locomotive with external gears respectively.

APPENDIX.

The Composition of Electric Locomotive Rolling-Stock.

There is one question of general importance to which the author would like to draw the attention not only of electrical engineers but more particularly of railway engineers, namely, the composition of the electric locomotive rolling-stock necessary to operate a given service. In using the term "a given service" the author intentionally makes a mistake, against which he would like to warn all those who may have to study the question but who have had experiénce of steam or electric traction only on tramway or underground systems. If the service to be maintained were definitely settled, it would be sufficient to replace each steam locomotive by a corresponding electric machine, which would be capable of hauling, on a line having a given longitudinal section, the same weight of train at the same speed as the corresponding steam unit.

Assuming that the problem is put in this form, it is easy to show that the weight of the electric locomotive is always less than the weight of the corresponding steam engine (excluding the tender). The difference in weight depends much more on the type of locomotive than on the nature of the current used; and when we take, for comparison, machines of the tramway type with two motor bogies, so that we have a large number of motors of small power, we are considering the most unfavourable case for electric traction.

Anything we may say regarding the specific power of machines of the type B + B or C + C is thus equally applicable to machines having a small number of powerful motors, taking into consideration the large reduction in weight owing to the better utilization of material in powerful motors having a large number of poles.

Even for types BB and CC it is possible to build machines at 1 500 volts weighing less than 50 kg per horse-power of continuous rating. This is, for instance, the case with machines BB 101–180 of the Orléans Company weighing about 75 tonnes and capable of giving a continuous output of 1 500 h.p. (one-hour rating, 1 720 h.p.) With high-power locomotives like those of the connecting-rod type 2D2 of the Orléans Company a continuous output of 3 500 h.p. is obtained for a total weight of 130 tonnes, or about 37 kg per horse-power (continuous).

In steam engines of European manufacture, although the continuous output is much less well-defined than in an electric locomotive, we might say that it is difficult to go below 55 kg per horse-power, excluding the tender. Therefore, if we admit that for equal sustained power the weights of electric and steam locomotives are the same, we make an error which is altogether to the advantage of steam traction.

This first point being established, it is easy to show that in comparing their normal running characteristics the machines under consideration are suitable for the same service.

Fig. 22 shows the curve of maximum sustained output for a steam locomotive of the Mikado type having $4 \cdot 31$ m^2 of grate area and weighing, without its tender, 82 tonnes unloaded and $91 \cdot 6$ tonnes loaded. It is known that this curve is the envelope of a series of curves representing the tractive effort as a function of the speed, and is hyperbolic in shape.

The electric locomotives of the series BB 101–180 have been so constructed that when connected in parallel, corresponding to running with full field and with 40 per cent of full field respectively, the combined characteristic is similar to the output curve of the Mikado locomotive.

Examination of Fig. 22 shows, in addition, that curve C, representing the tractive effort which can be sustained indefinitely without undue heating of the motors, passes very close to the point of intersection of the characteristic for the BB locomotive at full field and that of the Mikado locomotive.

For speeds ranging from 50 to 70 km per hour the electric locomotive will thus be able to develop indefinitely a drawbar pull greater than that which can be obtained for a considerable period from a steam engine. By decreasing the gear ratio it would be possible to increase the power available at high speeds from the electric locomotive and to show a still greater superiority over the steam locomotive.

At starting, the electric locomotive, which is of the total-adhesion type, will be able to develop a tractive effort higher than, or at least equal to, that of the steam locomotive, which has generally some non-coupled axles; in fact, in the case in question the weight on the driving wheels is slightly lower for the Mikado locomotive than for the BB locomotives.

We have, therefore, grounds for saying that for equal weights a direct-current locomotive can, even if considered from the most unfavourable aspect, replace a steam locomotive, its adhesive weight being in general higher and its power always considerably greater.

Assuming, to facilitate comparisons, equal weights, the first costs of the rolling stock will be:

$$\Sigma NPp \text{ for steam traction, and}$$
$$\Sigma N'Pp' \text{ for electric traction,}$$

where

N = number of steam engines,
N' = number of electric locomotives,
p = cost per kg of steam engines,
p' = cost per kg of electric locomotives, and
P = weight of locomotives, whether steam or electric.

In general, the cost of the tender is one-quarter of the cost of the locomotive, its weight being about $0 \cdot 5\, P$ and the price per kg about $0 \cdot 5\, p$.

The total cost of the steam engines in working order will therefore be $1 \cdot 25\, Pp$.

For high-tension direct-current machines the cost p' per kg of the electric locomotives is about 70 per cent higher than p. Notwithstanding alterations in economic conditions, this ratio, $1 \cdot 7$ to 1, seems to have remained constant, being the same before and after the war.

In order that the cost of construction of electric rolling stock shall be less than that of steam rolling-stock, it is necessary to have

$$\Sigma N'(1 \cdot 70 Pp) \leq \Sigma N(1 \cdot 25 Pp)$$

or

$$\Sigma 1 \cdot 36 N'Pp \leq \Sigma NPp$$

This condition will be satisfied in every case if the average mileage of the electric locomotives exceeds by 36 per cent the corresponding mileage of the steam locomotives.

Electric locomotives being always available, except in the case of repairs, their average mileage is considerably higher than that of steam locomotives, the tubes of which must be periodically scraped and the clinker removed from the fire grates. It appears, therefore, that the first cost of electric locomotives will always be less than that of steam locomotives if we assume that the two types of rolling stock have equal " useful service capacities."

In investigating as a whole the electrification of the system, the problem takes, however, an entirely different form. It is not a question of ensuring a clearly defined service, or of knowing what certain steam locomotives can do, in order to try to do as well or better electrically: it is really a question of ascertaining what is the general tendency as regards methods of operation on European railways, in order that provision may be made for the probable service conditions in future, taking into account the effect which electric traction may have on the operating methods themselves.

One might discuss at length the speed and extent of such developments, but the author thinks that he is not going too far in assuming that still heavier and still faster trains will be used in the future. Indeed, he considers that great developments in that direction would already have been made if the horse-power of a steam engine had not been limited by the boiler, the dimensions of which would seem to have practically reached their limits.

All the European railway systems are now taking steps to strengthen their carriage and wagon couplings, and within a short time some systems will consist only of vehicles fitted with 70-tonne standard couplings. Such apparatus would appear to allow a sustained tractive effort of about 20 000 kg. Already in Sweden and Norway, with special material, locomotives able to develop a sustained drawbar pull of 27 000 kg are used.

The application to goods trains of automatic brakes—at present under consideration in all European countries, and in use in a few—will allow the practical use of longer and heavier trains than those foreseen at the present time.

In accordance with a more or less settled programme, work is in progress everywhere in connection with the reinforcement of the track, with a view to allowing an increase in axle loads and in average speeds, without there being any necessity for exceeding the maximum speeds of 120 to 130 km per hour now obtainable with steam locomotives. Already in Switzerland, as in France (Paris–Brive line), it has been possible to increase to 20 tonnes the maximum load per driving axle of the electric locomotives, thus enabling us to obtain :—

Exceptional and momentary tractive efforts of 20 tonnes × 25 per cent, i.e. 5 000 kg per driving axle, using sand if necessary at starting ;

Sustained efforts (one-hour rating) reaching 12 to 16 per cent of the adhesive weight, according to the gear ratio, i.e. 2 400 to 3 200 kg per axle ;

Continuous efforts (continuous running) of 9 to 12 per cent of the adhesive weight, i.e. 1 800 to 2 400 kg per axle.

The feasibility of the above developments naturally points to the use of locomotives similar to those designed by the Orléans Company, leaving out of consideration the special suburban service, for which multiple-unit motor-coach trains will provide not only an increase in speed and comfort, but more particularly a valuable increase in the capacity of the Quai d'Orsay terminus.

Goods locomotives.—For goods trains, the nominal speed of which is never anywhere higher than 55 km per hour and frequently falls, as in the United States, to 25 km per hour, there is no reason why total-adhesion locomotives should not be used systematically.

Experience having proved that it is possible, by adopting forced ventilation, to construct motors having a continuous output of 300 to 400 h.p. (1 800 to 2 400 kg at 45 km per hour), there is really no reason why, on account of the facilities it affords for maintenance and repairs, the tramway type with 4-wheel or 6-wheel bogies should not be adopted, notwithstanding its higher price and weight.

For these reasons, on the chief railway systems in France, namely the Ouest-Etat, the Midi and the Orléans Railways, type BB total-adhesion locomotives have been adopted, with free bogies in the case of the Ouest-Etat and most of the Orléans locomotives, and coupled bogies for the Midi Railway and some locomotives of the Orléans Company.

On the Orléans Railway the normal goods-train locomotive comprises two type BB machines coupled together, and such a double locomotive will be able to develop a continuous effort of about 20 000 kg at 45 km per hour.

On the line from Paris to Orléans most of the goods trains, the average weight of which is over 700 tonnes, can be hauled by one BB machine, the use of the two-unit normal locomotive being reserved for the heaviest trains, in which case one crew drives the two half-locomotives from a single control position.*

Although these locomotives have no bogies or bissel-trucks, they have run on the three systems at speeds as high as 100 km per hour without undue effect on the track or material. This is not surprising, as the old 50-ton BB machines of the Orléans Company, built in 1899, attained about 20 years ago speeds higher than 100 km per hour on the line from Paris to Juvisy.

On certain American tramways, as well as on some French suburban lines, speeds of over 100 km per hour are attained daily with type BB electric motor coaches of 12 to 20 metres length, and it is of interest to recall the well-known Zossen experiments made in 1901–1902, when speeds of 200 km per hour were reached with electric motor coaches of the total-adhesion tramway type with two motor bogies of the 4- and 6-wheel type.

The stability of high-speed type BB machines is such that there is a possibility of extending their use

* The Orléans Company has also had under consideration the question of using double trains formed by coupling together two half-trains of 500 to 700 tonnes each, and of having two locomotives, one in front and the other in the middle of the train. Tests have also been made, with very encouraging results, with a view to the installation of a control system in which distant control can be effected by means of high-frequency currents (3 000 to 10 000 periods per second) superimposed on the traction current.

to the hauling not only of slow trains, but also of a certain number of express trains running at nominal speeds of 70 to 75 km per hour (maximum speed, 100 km per hour).

High-speed locomotives.—It is just as difficult to determine the type of high-speed locomotives as it is easy to settle the type for goods and ordinary traffic. At the present time, nowhere in the world is there a high-speed electric service for passenger traffic, and the tests made on certain systems, although very interesting, only supply incomplete information as to what may be expected from electric tractors.

an electrified line as possible. For the present, as there was available only about 60 km of 4-track line for our tests, we have been able to obtain information merely in regard to the general operating conditions of the locomotives, running stability, smoothness of the transmission system, and output of the locomotives in practice; and it will be necessary to wait several months before we are in a position to make a final choice between the various types of machines tested.

The author proposes here merely to indicate how these locomotives have been designed, as regards their power and their electrical characteristics, and he con-

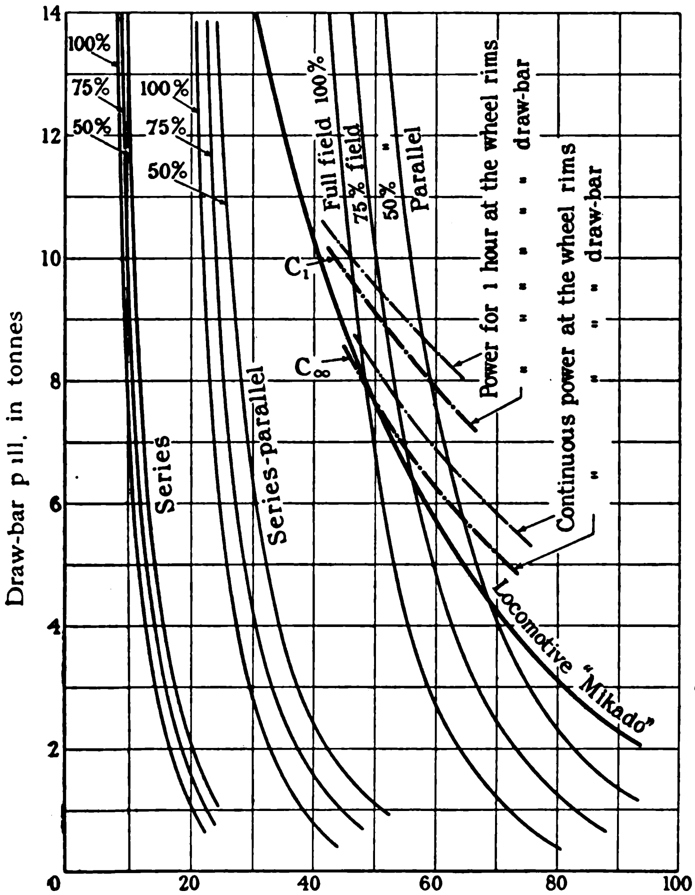


Fig. 22.—Curves showing drawbar pull and motor characteristics at 1 350 volts for locomotives of type EBB 101–180.
Gear ratio = 3·47. Diam. of wheels = 1 350 mm (53 in.).

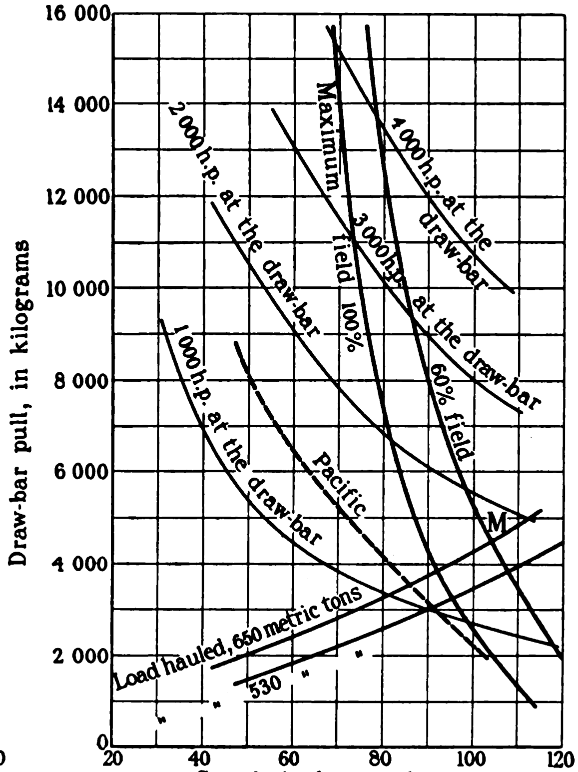


Fig. 23.—Curves showing drawbar pull of high-speed steam and electric locomotives.

At the present time, to speak only of French railways, express steam trains are running on the Nord, Est, P.L.M. and Orléans systems at average speeds of 95 to 100 km per hour, and the steam locomotives run distances of from 300 to 400 km without any stop being necessary.

The high-speed electric locomotive, as we conceive it, must, however, be able to maintain for the same maximum speed a higher average speed than the steam engine and over much greater distances, such as 600 to 1 000 km per day.

The problem thus defined can be solved only by arranging for time tests on regular services for as long

siders it preferable not to go further into their mechanical characteristics, the arrangement of the tracks, and the transmission system (which differs for different machines). He would refer interested engineers to his paper, mentioned on page 893, which is to be published in the *Revue Générale des Chemins de Fer*.

The tractive effort and the speed characteristics which have been decided on are about the same for the four locomotives of the type 2D2. Their construction has been governed by the conditions which allow a train of 650 tonnes to be hauled on the level and in a straight line at a speed higher than 100 km per hour. As the

maximum weight now accepted on the Orléans system for express trains is about 530 tonnes, we believe that sufficient provision has been made for any future requirements.

Fig. 23, in which curves have been drawn representing the tractive efforts necessary to haul trains of 530 and 650 tonnes at various speeds, also shows the running characteristics of locomotives of the type 2D2 of 3 500 h.p. continuous output with maximum field (100 per cent) and reduced field (60 per cent). The latter curve goes through the point M of the resistance-output curve of the 650-tonne train, corresponding to 104 km per hour.*

In the same figure has been drawn, for comparison, the curve representing approximately the maximum tractive effort at the drawbar hook of the tender of a Pacific engine of the Orléans Company weighing (including its tender) approximately the same as the connecting-rod electric locomotives of the type 2D2.

The comparison of these characteristic curves shows that for all speeds from 90 to 110 km per hour the useful power obtainable continuously at the drawbar hook of the electric locomotive is about 2·5 times greater than that obtainable at the drawbar hook of the tender of the steam engine.

For lower speeds the difference would be still greater, as the motors of the connecting-rod locomotive can supply continuously about 3 500 h.p. at speeds from 70 to 85 km per hour.

A very important margin of power has been provided, which enables tractive efforts of about 10 000 kg at 80 km per hour to be obtained at the hook, in order to be able to maintain that speed on the 1 per cent up-grades which are encountered rather frequently south of Limoges on the Paris–Brive line. Already, with a locomotive fitted with outside-gear drive and weighing 116 tonnes, we have been able to haul between Paris and Etampes a 650-tonne train at 120 km per hour, and at this speed the locomotive runs with a smoothness comparable with that obtained with the best bogie coaches.

Fig. 24 shows two records obtained at high speed with the Hallade recording apparatus, one on locomotive 2D2–501, and the other on a 4-wheel bogie coach. It is hardly necessary to draw attention to the fact that it is impossible, on account of the amplitude of the pendulum blades, to take similar diagrams in front of the engine of a Pacific locomotive without damaging the apparatus.

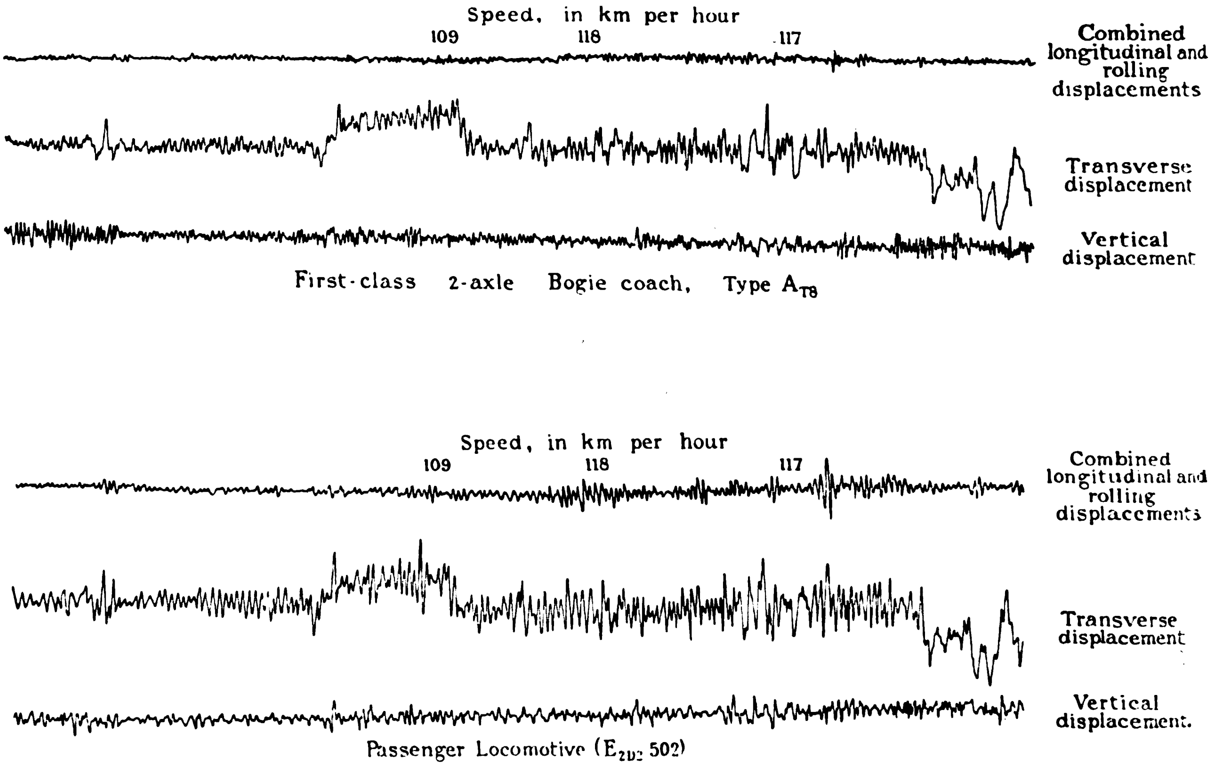


FIG. 24.—Records obtained using the Hallade apparatus.

From tests made with other types of machines, on the Orléans Company's tracks or on the tracks of manufacturers, it may be hoped that all the machines tested will comply with the electrical and mechanical conditions set forth in our specifications, and it is almost certain that all the transmission gears under consideration have proved, or will prove, satisfactory on official tests. Encouraging as they may be, however, these tests will not allow us to make a final choice between the various types under consideration until each locomotive has run a distance of between 100 000 and 120 000 km (62 000 to 75 000 miles), which in our opinion is the average mileage we should obtain per annum from a high-speed electric locomotive.

* Attention must be drawn to the fact that if we know merely the position of the point M, we can almost completely define the characteristics of the motor with reduced field (60 per cent) and maximum field (100 per cent) for small changes, due in direct-current motors to variations of the saturation and of the air-gap.

DISCUSSION AT A JOINT MEETING OF THE INSTITUTION AND THE BRITISH SECTION OF THE FRENCH SOCIETY OF CIVIL ENGINEERS, 18 FEBRUARY, 1926.

Mr. Roger T. Smith: If a diagram time-table be drawn, the ordinates being time and the abscissæ distance, dotted lines representing goods trains and full lines passenger trains, it is clear that where there are two sets of trains, one running at less than half the speed of the other, the greater the parallelism of the sloped lines representing the high and low speeds, the more trains can be put into that time-table. Ideally, to get the greatest use out of a given investment in the permanent way and stations, all the time-table lines should be parallel, but of course this is never possible. The steam locomotive is a constant-output machine, and a characteristic curve of the Orléans Mikado locomotive, of which the English equivalent is the 2–8–2, is given in Fig. 22. That shows, as compared with the BB electric locomotive, which is standardized in France for goods and slow traffic, that an increase in drawbar pull results in a very much greater decrease in speed in the steam locomotive than it does in the electric locomotive. Between 5 tons and 14 tons of drawbar pull, as shown in Fig. 22, there is a comparatively small decrease in speed in the electric locomotive, i.e. from 60 to 45 miles per hour; whilst for the same range of drawbar pull—that is, from 5 to 14 tons—there is in the corresponding steam locomotive a fall of from 40 to 15½ miles per hour. Special design can reduce the electric drop in speed if necessary. As an ideal which might be realized, if all the fast traffic ran at 100 km per hour (62 m.p.h.) and all the slow and goods traffic ran at 70 km per hour (40 m.p.h.) many more trains could occupy the line than is the case with steam haulage, and the boiler of the steam locomotive to do this, if it were possible to make it, would be very uneconomical. Electric traction gives railwaymen the opportunity of considerably increasing the traffic on congested parts of their main lines, and it is this aspect of the advantages of electric traction which is really important—the fact that the speed of the slow traffic can be so increased as to make the occupation of existing lines much greater with electric traction than with steam traction. It is a point which should be emphasized and driven home to the traffic officials and the management of our railways. The author has explained the reason which made France intent on preventing the import of coal as far as possible and designing hydro-electric stations and water storage for a combined supply for railway electrification and for industrial and domestic use. The seasonal variations in output of the hydro-electric stations supplied by rivers in the Central Plateau are largely balanced by the opposed seasonal variations from the stations in the Alps, which take their water from the melting of glaciers and of snow in the summer. This balance is incomplete, however, and the deficiencies are made up by steam stations in Paris which are interconnected with both types of hydro-electric stations already mentioned. This interconnection in France is essential, but is enormously costly, and would never be undertaken, I venture to think, if it could be avoided. The interconnectors feed the railways all along the route, but for industrial supply there is nothing between Brive and Paris except the town of Orléans. Just now in this country, when it is rumoured that a large system of interconnection of steam stations is proposed, and where there is little difference in the shape of the annual and daily load curves, the French problem is, I think, particularly interesting to us. All interconnection has to be paid for, and there is a natural form of interconnection when the transmission lines of two systems spread until they meet. Interconnection is then obvious, and the interconnector supplies load along its length. Some people in this country, however, hold a theory that there is economic merit, as well as technical merit, in what I may call idealistic interconnection as opposed to natural interconnection when two great centres of electric production in different areas are linked up by cables able to transmit large loads. I very much doubt if the economy of this has ever been proved.

Lieut.-Col. H. E. O'Brien: The author refers to the tonne-km per kilometre. It is important to know whether these tonne-km are gross tonne-km, including the weight of the locomotive, or whether they are net tonne-km, merely the weight of the train behind the locomotive. In discussing electrification problems it would be of great assistance if these densities of traffic could always be expressed more definitely as net or gross tonne-km per track mile, it being defined clearly whether or not the track mile includes the mileage of sidings: it is a matter of great interest to know the ratio between the amount of sidings and the amount of main-line track which has to be electrified, for this has a very important bearing on the cost of the electrification. In the Appendix the author shows that the charge for electric locomotive stock is not a capital charge; in fact he shows that for equal services the electric locomotive costs less than the steam locomotive. If the electric locomotives are provided on renewal account in the course of normal renewals—which, of course, would be the sound financial policy to adopt, even though it may temporarily involve a heavy overdraft on the renewal fund—the cost of the renewals ought always to be based on the provision of haulage capacity equal to that of the steam locomotives displaced. If, in making the renewals, the haulage capacity of the locomotives is increased, the capital is actually being increased. Therefore, if for equal haulage capacity the electric locomotive costs less than the steam locomotive which it replaces, it appears to me that there can be no question of there being any capital expenditure in connection with that part of the electrification. If, in addition, current is purchased from an external source and supplied to the railway, the sole capital charge that arises in connection with electrification is the capital charge in connection with the equipment of the track. I should like to ask the author, in

connection with the very high voltages employed for feeders, what precautions have been taken in regard to communication services—telegraphs and telephones. At what distance from the telegraph lines has it been considered necessary to run the high-tension lines, and how far in general are they from the railways? In connection with the locomotives, it would be of the greatest interest to see the result of the author's experiments. He is rendering a very great service to the electric traction industry in making these extensive experiments with such different types of locomotives. It is probable that the type which does not employ connecting rods of the large type will be the most successful, apart from certain other limitations which the outside-gear type has in regard to gear ratio. It has been emphasized a good many times in discussions on electric traction in this country that where there are brasses there are fitters, and fitters mean maintenance. Anybody who has seen the results obtained on locomotives similar to the 2D2 type will be inclined to think that that type will prove to be the best. It would also be of interest if the author would say something about the anticipated cost of current in his reply, because there is a general impression that electricity generated by water power is extraordinarily cheap compared with electricity generated by coal. That is not necessarily the case, at least at the point of delivery to the track, and it would be a pity if it was thought generally that these electrifications in France were merely due to the fact that there was extraordinarily cheap water-power-generated electricity available. It is credible that the third rail fulfils its function admirably, but it seems to be a very complicated and expensive design compared with the recent under-contact third-rail designs, which have a very much simpler type of guarding and are equally effective in protecting the rail against snow and ice, and also in protecting the staff against danger of shock. The author seems to have demonstrated very clearly the immense superiority of the electric locomotive over the steam locomotive. One is almost tempted to say that the electric locomotive is as superior to the steam locomotive as the steam locomotive in its early days was to the stage coach.

Mr. F. Lydall: One of the principal questions referred to by the author is whether an electric railway scheme should draw power from its own power station or whether it should rely on the general power supply of the country or of the area through which the railway runs. The author has mentioned various countries in which the practicability of drawing from the general supply is more or less excluded, and he has mentioned other countries where the conditions make it quite feasible to take power from the general source. In this country, opinion is not quite unanimous on the matter. I may put the position like this. Many railway engineers feel that security of supply is of the first importance and that the actual cost of power comes second. There is no doubt that that is a very important consideration from the railway point of view. They are charged with transport, and it is essential that they should make absolutely sure, so far as is possible, of security of supply. On the other hand, there is no doubt that there are advantages, financial and general, in taking the supply from a general system; but it is essential that the management of that general system should be absolutely sound, the reliability unassailable and the commercial, technical and financial position of the supply undertaking beyond reproach. There are also advantages quite outside the question of the position of the railway in the matter of taking the supply from the general source. Some of these are referred to by the author. There is no doubt that the combination of a railway load with the general load is to the good of the country at large. The author has really set out these two alternatives in his paper, and he has shown us the way in which the Orléans Railway has solved the problem. It has not only its own power station, but is also taking supply from the general source; in fact it has set itself up as part of the general system. This is a very bold and interesting method of attacking the problem. The circumstances, of course, must differ in every country, and the conditions in France which have led up to this solution are perhaps quite peculiar and do not necessarily apply to other countries—certainly to this country. There is another point about this description, namely, the very great extent of the electrification scheme. This has a marked effect upon the point I have just been mentioning, namely, the general question of power supply. There has been in the past a good deal of tendency in this country to regard electrification of railways as something to be nibbled at. "Let us electrify a bit of main line first. We will deal with a section of 30 or 40 miles, and if we get good results out of that we can go on with another 10 or 20 miles," and perhaps in the time of our grandchildren we shall get to 200 miles. The drawback of that method is the probability that the first 30 miles will not show any advantage, and that will be the end of it until someone points out that the problem is being tackled in the wrong manner. The Orléans Railway has started off with a very big scheme, which will enable the advantages to be reaped at once. There are many difficulties in getting the full advantage of electrification schemes on a small scale. In the first place there are traffic disadvantages, and in the second place there are the disadvantages in regard to cost of power and of all the plant which must be used on rather a small scale. Therefore I think that this particular railway-electrification scheme is an example to many as to how electrification matters should be dealt with. It is not always realized that the power demand in electrification schemes is comparatively small. The position is that for any particular scheme the kilowatt demand is very small and not necessarily a very attractive proposition to put before a supply undertaking. In regard to the scheme referred to in the paper, the estimated annual demand is 400 million units, with a maximum demand of 80 000 kW. That 80 000 kW must be a fairly steady demand. It is made up necessarily of the demand of a large number of comparatively small individual units taking power intermittently. This question of the intermittent demand is a very important one in railway-electrification schemes. There is a modern tendency to increase the size of railway trains. A railway train necessarily is less expensive to run from the staff point of view if it is

increased to its maximum capacity. That in itself means that the power demand for a single railway train is as much as can be practically utilized on a single unit, and for any given traffic the number of units is reduced to the minimum. This leads to large and frequent variations in the demand for any scheme. For instance, it is not at all uncommon in schemes to find that at a moment's notice 3 000 or 4 000 kW is thrown on or off. It comes to this—that for a comparatively small scheme the intermittency of the load is, or would be, a serious matter if the demand had to be supplied from a single station erected for the purpose. Where the supply comes from a large organized system of general supply, such fluctuations are of relatively little importance. As an illustration, I may quote some figures which I have recently obtained from a main-line electrification scheme. The average demand over a single week was 9 500 kW. The sustained maximum demand was 17 000 kW, and the 2-minute maximum 25 000 kW. This was a main-line scheme in which the traffic was constantly flowing throughout the day and night; it was not like a suburban scheme in which the traffic was all bunched up in a few hours. A diversity factor of nearly 3 is very undesirable. There are a few points in regard to the traction part of the paper which I should like to mention. In Fig. 5, which shows the number of trains on various parts of the system, and also other figures showing the number of trains on the branch lines, there are certain peaks; that is to say, in certain parts of the line there are more trains than others and, so far as I can see, those peaks seem to occur where the gradients are severe. I am not quite sure whether that indicates that heavy trains are broken up at those points into two parts and taken up separately, or whether it indicates local traffic which does not travel beyond the limits of a suburban system at that point. In the Appendix the author gives details of horse-power and weights of locomotives, but I think it is inadvisable to lay too much stress upon this point. There can be at present no standard value of tons per horse-power. It depends largely upon the duty of the locomotive. The locomotive may have to haul very heavy goods trains at comparatively low speeds, and will have to deal with very heavy drawbar stresses and so on. On the other hand, it may be a comparatively high-speed locomotive with a small draw-gear strength and a comparatively high horse-power. The details have to be taken into account. In some cases it is necessary to increase the weight by means of cast-iron ballast in order to give the necessary adhesion. When the various details of the locomotives to which the author refers in the Appendix are available, they will be a valuable assistance in the direction of arriving at a sort of general standardization system for locomotives—not depending on the weight per horse-power but upon the duty they have to perform in several different ways.

Mr. F. W. Carter: One of the most valuable points about this paper is that it deals with an ordinary railway. Most of the problems with which we have hitherto had to deal in connection with electrification of railways have been in some way special; some exceptional difficulties have induced the electrification. In some countries, such as Sweden and Switzerland, it is a question of shortage of fuel; in others it is a question of dense urban traffic, such as we get around all our big cities. In others again it is a question of heavy gradients—the Norfolk and Western Railroad, the Virginia Railroad, the Chicago, Milwaukee and St. Paul's Railroad may be quoted as examples of this. Sometimes, as in the Detroit River Tunnel and Mt. Cenis Tunnel electrifications, it is a question of long tunnels in which the noxious gases are troublesome. The Orléans line, however, is a plain normal section of line, without any of these exceptional features. It might be a section of the London, Midland and Scottish Railway, and its working is exactly the kind for which the steam locomotive was developed, in which it is seen at its best, and in which, in the opinion of many railway engineers, it is still without a rival. If this electrification proves an economic success, it will have been attained under conditions which apply to a great part of the world's railways. If it can be made a success it should provide a big impetus towards general electrification. What is the chief obstacle to electrification under the conditions of this country? It is the great capital burden of electrification. No one is willing to make a start when there is so much capital involved. The French railway engineers have shown the way of meeting this to a large extent by taking the burden of generation and transmission from the railways and including it in the ordinary industrial electrification of the country. This seems to me a step in the right direction, particularly as the railway load is an advantageous one to mix with the industrial load on account of its good load factor.

Mr. A. M. Taylor: I have already, in the discussion at Birmingham,* emphasized the supreme importance of employing the very highest voltage in long-distance transmission, and French railway engineers are to be congratulated upon their appreciation of this all-important factor. I have also pointed out that unless powers of the highest magnitude, transmitted at the very highest voltages, are employed, the fixed charges on the overhead line will give the impression that long-distance transmission in Great Britain is impracticable, because of the comparatively small differences in the cost of power at the two ends of the line, due to the fact that we have no water power in this country. This point is not generally appreciated, as will be manifest from the fact that Mr. W. E. Highfield, in an informal paper read a year ago before the South Midland Centre of the Institution, gave figures to prove that the transmission of 20 000 kW could not be effectively carried out for a distance greater than about 36 miles, based upon the employment of steam power at both ends of the line, and upon the difference in cost in power, the power being transmitted from a large station to a small station. I showed in my contribution to the Birmingham discussion on the present paper that if we consider the transmission of as great a power as 125 000 kW over 100 miles, and with two big stations one at either end of the line, it will pay to do it, provided that the one station generates power at, say, 10 per cent more than the other station, or, to take a concrete

* See page 914.

case, at 0·5d. and 0·45d. respectively. This example applies with greatly increased force if a group of small stations be taken and the question of transmission of power from a large station 100 miles distant to this group be considered. Why cannot the Government and the railway companies combine in a similar way as has been done in France, the railway companies helping to find the capital outlay for the overhead line, which would follow the route between important centres, for example between London, Birmingham, Manchester, Liverpool, Carlisle and Glasgow? Another point of considerable importance is the question of what is known to transmission specialists as "stability" of the overhead line. When large, sudden increments of current occur on a long-distance overhead line, the phase of the voltage (expressed vectorially) swings round, for example, in an anti-clockwise direction, while the phase of the current swings round in a clockwise direction, and when, for example, synchronous apparatus at the receiving end of the line (the phase position of which cannot change instantaneously) is suddenly confronted by a heavy displacement of the voltage, the apparatus is liable either to hunt or to fall out of step. The action is not dissimilar to that which applies when a synchronous motor has a sudden load thrown upon it, causing a phase displacement of the machine with reference to the impressed voltage, causing a break-away. I note that, although the author has a very long line to deal with (280 miles), the only provision for synchronous condensers appears at present to be at Chaigny, a place comparatively near to Paris, and therefore quite out of accordance with the most recent findings of our transmission experts in America, who maintain that the best position for the synchronous apparatus is midway along the line (or preferably distributed along the whole length). Then, also, the amount of synchronous apparatus provided for is, it would appear, quite inadequate for the expected loads, unless it is proposed to increase these synchronous capacities very materially. What I have to suggest is that, with all respect to French railway engineers, the position of the phase-rectifying station is wrongly chosen, and secondly, that the amounts of synchronous power put down are insufficient to avoid serious power limitations on the line, from the point of view of stability. On this same question, I may say that a careful study of such papers as those by Fortescue and Wagner, Shand, Evans and Bergvall, Baum, etc., makes me feel fairly confident in stating that, on the question of stability, applied here in Great Britain, it would be unnecessary when connecting two steam stations 100 miles apart to provide any synchronous condensers whatever—unless perhaps a small amount for adjustment purposes—and in these circumstances one of the gravest disabilities of high-tension transmission disappears. (I may say that this disability is not so obvious where cheap water power is at issue, but is serious where we are transmitting from a steam station to a steam station.) Even this disability, however, is largely countered by the employment of the very highest voltages.

Mr. E. M. Malek: Anyone who has been associated, as I have to some little extent, with railway electrification, must be struck by the fact that the French railway engineers have not only grasped that the first essential for railway electrification is a general supply of energy available everywhere and anywhere in any quantity, but that they have been able to co-ordinate the various public and private interests in such a way as to produce a workable scheme. The author mentions that his railway is only a part of the scheme. At various times French Cabinet Ministers have declared it as the policy of the Government that electricity is to be widely distributed, and that the electrification of railways and everything else would follow. I think that that is right and that main-line railway electrification will follow and not precede general electrification. The problems involved in electrifying small sections of line under special conditions can be solved in various ways; in some alternating and in others direct current may appear most beneficial. If any railway is taken as a whole, however, it will be found that the capital expenditure on power development and distribution—irrespective of the sort of current used for traction—is so enormous that the companies cannot face it, and unless they can be freed from this great interest-bearing charge it does not appear to me that electrification can ever become general. The author seems to believe that the possibilities of the electric motor will lead to an increase in train weights, but I am not so certain on that point. Existing railway working has been built up around the steam locomotive. When railway officials know more about the advantages and use of electricity, and are faced, as they will be, with greater competition from road transport, it is possible that their views on the advantage of infrequent and heavy trains will be modified. French engineers are always willing to spare time and give the results of their experience to English engineers actively interested in railway problems, and if they took advantage of this to study the subject there, I am certain that they would obtain much valuable information applicable to the problems which they will have to face in this country.

Sir Philip Dawson (*communicated*): We are one of the few industrial countries who have little or nothing to show as regards main-line electrification. Incidentally we learn that the first and most important section from Paris to Orléans will be supplied by the steam-driven stations of Gennevilliers and Vitry, thus confirming the experience gained in the United States and Germany, that main-line railway electrification may profitably be undertaken where, as in this country, the current is generated by steam-driven plant. This is a practical confirmation of the results which I worked out would accrue if the line from London to Brighton had been electrified (published in the paper which I read at the World Power Conference in 1924), and of the figures given by Col. H. E. O'Brien in his paper.* I hope that the author's opinion that "Great Britain would appear to be on the eve of extensive electrification" will prove to be correct. Another very interesting statement of the author's is that although the pressure adopted is 1 500 volts, with the exception of the suburban area the whole contact system is an overhead one. He gives very cogent reasons for this, which apply equally in this country. From these it would seem that even if

* *Journal I.E.E.*, 1924, vol. 62, p. 729.

the pressure is limited to 1 500 volts, overhead conductors will have to be adopted. It would be very interesting to know whether the author, if he were to start now with a free hand, would not adopt a pressure of 3 000 volts, which is what has, I understand, under his guidance been adopted for the main-line electrification now proceeding in French Morocco. The great benefits which main-line electrification will bring about in the cheaper generation and widespread transmission of electricity over areas which, but for electrification, would not justify the cost of transmission lines, are very clearly brought out and confirm the views I have so often expressed of the benefits this country would reap from properly conceived proposals to electrify selected portions of our railway system. There can be little doubt of the practical advantage to be gained in this country from the standardization of generation and transmission. In this country, as in France, the general direction of main transmission lines will usually coincide with that of railway lines having the densest traffic, where the question of electrification is also of most interest. The electrification of properly selected sections of main-line railways in this country should be just as beneficial here as in France, where the author states that the realization of vast electrification proposals constitutes one of the most efficient means of re-establishing stable conditions. The author says that before the end of this year the 124-mile section, Paris to Orléans, will be entirely electrically operated and that electric traction will replace steam for the whole of the passenger, goods and shunting services. Many of us are envious that in this direction we lag so far behind. As regards substation plant, rotary converters, two in series, are to be used. For 3 000-volt lines rotary converters are not practicable, and it is fortunate that we have the mercury rectifier, which possesses simplicity of working, very high overall efficiency at practically all loads, and great overload capacity. It is no longer in the experimental stage, as the results on the Midi Railway and on the Turin-Lanzo line definitely prove. Another fact brought out by the author is the very high load factor of a main line as compared with that of purely suburban electrification. His results fully confirm those arrived at by Col. O'Brien and myself, that a load factor of at least 40 to 50 per cent may be expected in the case of any main line on which electrification can be justified on economic grounds. In view of the Electricity Bill which will come before Parliament this session, the author's statement that the French Government is considering a programme for linking up the various distribution systems, rather than Government generation of electricity, is most interesting and instructive. His remarks on electric locomotives on the whole confirm the view which is now being very generally adopted by those who, like myself, have made a continuous and detailed study of the electric locomotive—that with few exceptions to-day a connecting-rod drive for high-speed locomotives is losing ground in favour of some form of individual drive through spring gears. For lower-speed locomotives for handling local passenger and goods trains the tramway type seems eminently suitable, whilst for high-speed locomotives existing spring motors, either individual or twin, located above the axles are rapidly becoming the standard. In this connection the twin vertical motor driving a hollow shaft connected by springs to the driving wheels through bevel gear is most interesting, and the results this type has achieved on the Midi railway are well worth a careful study. The work done, more especially in Germany, by locomotives used for shunting purposes, and even by motor coaches supplied with current from accumulators, deserves careful attention, and it is quite conceivable that such locomotives might form a most useful adjunct in connection with main-line electrification in this country.

[The author's reply to the discussion will be found on page 918.]

South Midland Centre, at Birmingham, 17 February, 1926.

Mr. F. J. Moffett: As the Prime Minister pointed out in his speech at Birmingham on the 15th January, one most important desideratum for cheap and abundant supply of electric energy is a good load factor, and it is generally recognized by all electrical engineers that the readiest means of improving the load factor of our large generating stations is to provide an electric railway load. The proportion of the 24 hours during which a supply is required is far higher on the railway systems than in any industrial concern. Electrical engineers are, I think, agreed that there are no insoluble technical problems in connection with the electrical equipment of our main railway lines. The chief obstacle appears to be lack of capital. It would appear that it is just as feasible for our Government to provide loan facilities for this purpose as for the interconnecting trunk lines and standardization of frequency provided for under the new State electricity scheme.

The Southern Railway report gives no details of comparative costs for electrical and steam-train working, but it is believed, according to *The Times*, that the difference is considerable. Some of the figures given in the report may be of interest and may assist us in arriving at some sort of estimate of the effect of electrification. It may be remarked, however, that allowance should be made for the fact that much of the expenditure on electrification is so recent that the full effects cannot yet be judged.

Southern Railway.

Trains worked by electric traction.

1924	5 019 000 train-miles.
1925	7 605 000 train-miles.

Cars worked by electric traction.

1924	568
1925	1 162

Amount spent on electrical equipment.

1924	Nil.
1925	£397 000

Amount spent on new steam locomotives.

1924	£255 000
1925	£79 000

Total receipts increase in 1925: £423 325.
Total net income in 1925: £6 415 000.
Increase in 1925: £96 700.

Difference between net income and total of dividends and fixed charges in 1925: deficit of £212 900.

At the same time I came across the Great Western Railway report, and for the purpose of comparison I shall quote a few of the figures given. The Great Western Railway have not adopted electrification to the same extent as the Southern Railway.

GREAT WESTERN RAILWAY.

Total receipts decrease in 1925: £814 500.
Total net income in 1925: £7 107 000.
Decrease in 1925: £345 000.

Difference between net income and total of dividends and fixed charges in 1925: deficit of £1 187 000.

The Southern Railway therefore showed increases in total receipts and net income for 1925 over 1924, whilst the Great Western Railway showed decreases in both cases. The deficit for the Southern Railway is £212 900 as against that for the Great Western Railway of £1 187 000. It naturally occurs to me to wonder whether the partial electrification of the Southern Railway is responsible to a certain extent for the better figures shown.

Mr. A. M. Taylor: The interesting fact that here we have an example of the French Government combining with the railway companies in such a way that equipment is being provided for transmitting an initial traction load of some 40 000 kW from the source of water power at the Central Plateau to Paris, with a view to ultimately transmitting an additional 70 000 kW over a distance of not less than 280 miles, provides food for reflection. If it pays the French Government and the railway companies to consider the transmission of such a large amount of power over a distance as great as 280 miles, what difference in the cost of power, as generated at two different places in, say, Great Britain, will warrant a transmission of power in bulk from one to the other? In the case of the French transmission the fact that the power is to be obtained, and presumably fairly cheaply, from water power at the one centre, whereas at the other centre it is obtained from steam power generated largely by foreign-bought coal, no doubt explains the reason for the decision to transmit over such a great distance. It can be said that all the power in Great Britain is produced from coal, and the only question we have to consider is whether the cost of power at two centres, due to local circumstances or other factors which govern either the cost of coal or the capital costs of the stations, may sufficiently differ, even though coal is used in both cases, to warrant transmission from one to the other. I feel that on this question of long-distance transmission, engineers in this country have lost sight of three important points which have been fully grasped by engineers in other countries, who have had long-distance transmission forced upon them by the possession of water power. These three points are: (1) Unless we transmit *very* large powers over a high-tension line, the interest, sinking fund and repair charges are so high that an impression is at once produced that it only pays to transmit power over comparatively short distances. (2) The enormous benefits of operating at the very highest voltages, e.g. 220 000, have not been appreciated. Below this voltage the charges on account of energy lost in the line are higher than the fixed charges due to interest, sinking fund and repair charges. (3) It is only by the employment of the very highest voltages that the capital outlay on a long line, per kW transmitted, can be so reduced as to bring things into the realm of commercial possibility, on account of fixed charges on the line being otherwise too heavy. I have found that on a 100-mile line the interest, sinking fund and repair charges, when transmitting 125 000 kW on a load factor of 33 per cent, are only of the order of 0·025d. per unit, whilst the loss charges are as low as 0·017d. If we take a round figure of 0·045d. per unit as the total charges debitable to transmission on this scale between two towns, it will be seen that it would, for example, pay to transmit power from Birmingham to London, if the cost of power at Birmingham were 0·45d. per unit and the cost at London were 0·5d. Differences much greater than this frequently exist between the costs of power in our large centres. A group of small towns having individual small outputs might in a similar way be supplied from a large centre where the cost was cheaper, even if such centre were 100 miles away.

Dr. C. C. Garrard: I propose to approach the subject primarily from the point of view of how it affects the future of electric supply in this country. The author states on page 899 that "the greater the coal consumption per mile of line, the more favourable will be the financial results of electrification." Now I take it that the density of traffic, and hence the coal consumption per mile, are as great as or greater on British railways than anywhere else in the world, hence the author's general conclusion applies with increased force to British conditions. It is very interesting to see (on page 893) that the substitution of electric power for steam on railways is regarded by the French Government as one stage in a more comprehensive scheme. It is to be hoped that this view will find favour in the discussions on the Electricity Bill about to be introduced into Parliament. On page 896 the load factor of the French electric supply is given as 28 per cent, which is low in comparison, for example, with American conditions, but Fig. 2 shows clearly how the addition of a railway load would improve the load factor. As I take it that one of the chief hopes for cheaper supply under the British Government's proposals is based upon the securing of an improved load factor, this shows how important it is to include railways in the electrification

scheme. It appears to me, however, that the technical question of railway electrification has been settled; moreover, it has been proved, as far as any proposed commercial project can be proved, that it would pay. The difficulty in the way is, in my view, the conservatism of the railway directors. This difficulty has been undoubtedly increased by the railway amalgamations, which have rendered the railway companies more powerful and less likely to make innovations. The chairman of one of the railway companies stated recently that he did not consider it necessary to think about railway electrification for the next 10 years. If the Institution wishes to help forward railway electrification in this country, it must enlist public opinion on its side. Unfortunately, most of the British public do not realize what a very poor transport service the British railways render. The point I wish to bring out is that it is not possible to secure the greater comfort and convenience of travelling unless electric traction is adopted. Take, for example, the great majority of the terminal stations in London and our large cities. They are, to put it mildly, a disgrace, but it is very difficult indeed to do anything with them with the steam system. Unfortunately, I do not think the railway directors will be moved by reason. Therefore I welcome the competition of motor transport. Manufacturing companies already find it in very many cases very much better and cheaper to utilize motor transport for their goods rather than the inadequate service rendered by the railway companies. The same result is coming about to a larger and larger degree with passenger traffic. It is, however, in the long run economically wrong that the roads should be used for transport work that would be better done on railroads.

Mr. F. W. Carter: The contact rail shown in Fig. 18 appears to be a good mechanical job, but I have not hitherto met with a rail of the section shown. The contact tip being of small area would tend to cut the shoe in grooves, and I presume the reason for its use is that the shoe is able to keep the rail clear of ice. I note that some of the locomotives are equipped for regeneration; from the appearance of the gradient profile I should not have thought the advantage of regeneration worth the complication. The freight locomotives are of the 2-bogie type having all the weight on the driving wheels; this type is tending to become standard for this class of work. High-speed passenger locomotives are, however, less standardized, and I am glad to see that the author is to try out a number of types. I am sure the information he will gain will be valuable, and I hope he will be able to put it at the disposal of engineers generally.

Prof. W. Cramp: The great success with which the generating stations have been arranged to co-operate is a striking tribute to the spirit which animates the French electrical undertakings, and it would be of interest to know something about the Government machinery by which such co-operation has been rendered possible. The author states that the greater the coal consumption per mile of line the more favourable will be the financial results of electrification. It seems to me that the financial results will be influenced by the coal consumption per ton-mile as well as that per mile. With regard to transmission, it is interesting to note that the highest voltage adopted on any cable is 60 kV, and that single-phase cables are used. Does the author mean single-phase concentric or single-core cables? If the latter it would be very interesting to know whether they are sheathed with lead or armour, or both, and whether the cores are hollow. What is the maximum dielectric stress allowed and what is the insulating material? The general principles put down on pages 896 and 897 are of universal importance and are, I believe, stated for the first time here. The benefit accruing from the combination of the railways with the industrial load is mentioned but not proved. It seems as though the industrial load factor in France is higher than in England. For an industrial load without trams, 28 per cent is a high figure, except in a colliery district or in a region where there are large steel-works. With respect to the motor coaches, it seems that the goods locomotives have 1 500-volt motors, but for passenger trains it is considered more advisable to use two 750-volt motors in series. The power, however, of the goods motors is greater than that for the passenger coaches, so that it would seem that the disadvantageous series arrangement is due to difficulties of commutation at high speed. There must have been some good reason to lead to an arrangement which permanently reduces the efficiency of control. I should be glad if the author would state what steel is used for the contact rails. The effect of linking up hydro-electric with coal-fire generating stations will be closely followed in this country. The author gives no indication of the relative costs of generation in the two cases, nor of the manner in which the payments for energy are to be adjusted as between the various sources of supply. It is manifest that a coal-fired station cannot afford to give a stand-by supply at the same price as a continuous supply. In other words, the presence of a hydro-electric station would seem to make the load factor worse for the steam station, and since the former takes the cream of the load the latter should be paid more per unit supplied. Can the author say how these adjustments are to be made, and what proportion of the cost per unit is due to the very long feeder system? Finally, the author showed slides of very fine overhead line construction, but I noticed that the elaborate guarding which would be required in this country was conspicuous by its absence. The expense of this addition must not be forgotten when comparing the capital costs of distribution with those which would obtain in England.

Mr. J. D. Carlmark: The author states that "the greater the coal consumption per mile of line the more favourable will be the financial results of the electrification." This, I take it, would always be the case whether the supply is derived from water or steam power, as after electrification the railway should be worked more cheaply. Would not the density of traffic also reduce the capital and working costs per ton-mile, as with very little increase in the cost of line and transmission equipment much greater earning capacity would result and the station and other staff could deal more economically with the heavier traffic? Is this the reason for the saving in the coal consumption? I noticed that on the Paris–Vierzon section 330 000 kW will be

obtained from steam-power stations and only 200 000 kW is at present available from water-power stations, thus showing, even with steam-power plants, the financial soundness of electrification. It is interesting to note from Figs. 3 to 6 inclusive that the distance between substations varies from 4·4 to 26·8 km, but for the majority is about 21 to 25 km. The distance of 21 km (or approximately 13 miles) is very near to the spacing suggested by Col. H. E. O'Brien, of 12 miles between substations for an English main line. The working arrangement of exchange of power between the various water- and steam-power plants is very interesting and shows that a great deal of thought must have been expended on this matter. Similar circumstances in a smaller degree may occur between various steam plants in this country, and the matter is well worth bearing in mind, because of seasonable loads. Do the power transmission lines follow the railways, or are they run more for the convenience of the industrial load than for traction? If the transmission follows the railway, has there been or is there likely to be any electrical interference with telephone or telegraph circuits due to the 150–220-kV power circuits, or electrolysis from the d.c. distribution, and, if so, has a successful cure been found? The three-phase supply would of course balance much better than a single-phase supply, but the higher pressure may cause trouble. Fig. 7 shows a very interesting increase in the traffic; I take it that the author presumes that this will increase at a much greater rate with electrification. It is noticeable that France has departed from the Continental practice of providing power stations for the railway requirements only. This is, I think, a step in the right direction. A further description of the locomotives and their control gear, etc., would have been welcome, but probably this information will be included in the author's paper in the *Revue Générale des Chemins de Fer*. The results of the tests to be carried out on the high-speed locomotives should prove very valuable.

[The author's reply to this discussion will be found on page 918.]

North Midland Centre, at Leeds, 23 February, 1926.

Mr. R. M. Longman: The paper is of great value in several ways. It shows how the Government of one country has made an attempt to assist its industries generally. It is an attempt to combine and deal with the railway load and the industrial load, and it gives the results and investigations carried out in a country where conditions differ considerably from those in this country, but which would serve as a basis on which similar investigations could be carried out. We could adopt their methods, but nothing of the kind has been attempted in this country. We had a Coal Commission, but the result of their labours is by no means comparable with that of the French Committee. The statistics in Part 1 dealing with the transmission of power and the method of operation with the various sources of power supply are lucid and instructive. One cannot help comparing the attitudes of the Governments and the developments which have taken place in the different countries since the war. Germany, who lost the war in a military sense, but who suffered less material damage, set about and reorganized its industries by means which are in their way a greater catastrophe then the war. By their questionable financial operations they have reconstructed their industrial organizations. Practically all their works have written off their capital costs, and they are now able to go ahead without the burden of capital charges which this and other countries have to carry. The author has shown one of the ways in which the French have attempted to repair the ravages of war and the material damage, in which respect they suffered so heavily. They examined their chief items of import and decided to reduce as far as possible the importation of coal, which stands at approximately 17 million tonnes. They realized the advantages of combining railway and industrial electrification. They did not attempt to tax industries out of existence, whereas we have paid our way and paid our debts simply by taxing industry to the limit and at the same time maintaining a huge army of unemployed, which is a double tax on industry. On page 899 the author touches the kernel of the railway electrification question when he says: "It can easily be shown that the greater the coal consumption per mile of line, the more favourable will be the financial results of electrification." In paragraph 2 of the introduction he says: "At the present time, when Great Britain would appear to be on the eve of extensive electrification work." I assume that he intended to add "of railways," but I very much doubt whether we are on the eve of extensive electrification of railways. The grouping of the railways appears to have generally set back all electrification schemes. All energy seems to have been devoted to effecting small economies in staff and other ways of working, all of which are no doubt very necessary and helpful, but nothing in the nature of a more extensive scheme of electrification has been considered. I take the view that after the war we were in a better position to consider the electrification of some of the main lines and particularly those with the heavier traffic, for the simple reason that our rolling-stock and permanent way had got into such a bad condition—particularly the rolling-stock. Instead of providing a large number of new steam locomotives, electric locomotives might have been chosen, as their percentage time of active service is so much higher. Is the railway companies' conservative attitude similar to that adopted 100 years ago when machinery was being introduced into the mills? The transport of coal is a very big item of revenue to the railway companies. Are they afraid of losing it? To my mind the transport of coal, which at present is the life blood of industry, is an item the cost of which should be cut down to the lowest possible level. Again, we must consider the amount of coal used by the locomotives as compared with the amount of coal which would be used in large modern power stations to do the same work. I think that the ratio is more than four to one. We know that in a modern power station as little as 1·7 lb.

of coal has to be burnt per kWh. The general idea that transmission lines should follow the main railway lines is undoubtedly correct, as the railway lines are built where the traffic and the industrial requirements necessitate them. Turning to the technical items in the paper, I should like some further information as to the electrical plant. I notice that at Chaingy two 20 000-kVA transformer units are used to couple the 90-kV system with the 150-kV system. These huge transformers are star-connected on both windings and are provided with tertiary windings at 6 000 volts, to which are connected large synchronous condensers for providing the wattless component and regulating the voltage of the line. It is a most interesting arrangement and one to which I have given much consideration. I should also like to know what provision has been made for earthing the neutral points of the transmission systems, and whether they are earthed at more than one point. I do not know the methods adopted by the Post Office authorities in France, but I believe they find it is necessary and safer to earth the neutrals at more than one point. The arrangement of two 750-volt machines in series is the same as that adopted on the Shildon–Newport line and was adopted on several schemes by English firms in South America. I am rather surprised that they have not adopted converters giving 1 500 volts in one unit.

Mr. H. M. Taylor: I think it is important that we should realize the difference between the financial situation of the French railways and that of our own. In reading the paper the first impression one gathers is that the French seem to have done far more than we have done in regard to the electrification of the railways. I am told, however, that practically all the technical committees which have sat, and which have been drawn from the railway companies in France, have almost universally stated in their reports that from the financial standpoint there is no case for electrifying the main lines. Practically all the railway companies in France are subsidized by the Government. One of the large railways is actually run by the State. Apart from that, all the larger companies are still subsidized, and therefore there is no reason why they need trouble about paying their way. The steel transmission towers shown in the lantern slides are not painted; they are coated with zinc by a special process known as the "Schoop" process, in which the zinc is squirted on under compressed air. I have calculated that the cost of the zinc-coating is about five times the cost of the painting, and I should imagine that the painting is a considerable item in the annual cost.

Mr. C. J. Chaplin: The recorder used for obtaining the records in Fig. 24 was invented by Mr. Hallade, who was one of the divisional engineers and later chief engineer of the Est Company (France). This apparatus has been adopted on the North-Eastern system and was once tried on the London and North-Western system.

Mr. W. E. French: This paper presents, in my opinion, not so much an argument in favour of railway electrification in France, but rather an excellent exposition why Paris and its industrial area should be connected with the Central Plateau and the glacier reservoirs, electric traction being merely incidental and subsidiary to this main problem. France is rightly striving to reduce her coal imports, and so must make economical use of her great water-power resources. As the author points out, the chief power routes will chiefly follow the railways, which in consequence were drawn in to assist in the creation of a good load factor along this transmission line to Paris. The problem in Great Britain, at the present crisis in the coal industries, is different. There are no great sources of water power upon which we can draw, and both the railways and the electricity supply industries are dependent for power on our coal. I think that I am not understating the case in saying that with the electrification of the railways they would experience a reduction at least of 25 per cent in coal consumption. Considering the precarious state of the coal industries to-day it would seem that such a reduction would not be considered favourably by the authorities concerned, and the electrification of the railways must be a costly affair which, as previous speakers have pointed out, the railway companies simply cannot afford. It appears that the combined effect of these will retard for some considerable time the development of main-line electrification in this country. When main-line electrification in this country does come, it will be incorporated in a national scheme. That Germany, Switzerland and Italy developed two systems—one for traction and one for power supply—was simply due to the facts that they were pioneers and that public opinion on the question of electric power had not sufficiently developed to force a national demand, and further, at that period technical opinion was favouring single-phase traction and single-phase commutator motors. The latter of course demanded, from the point of view of commutation and power factor, a low frequency and the development of a low-frequency supply. Assuming national supply for power and traction, frequencies will be either 40, 50 or 60 periods; the battles of frequencies in this country will yet have to be fought, although official opinion has already pronounced in favour of 50 periods. Whatever the standard frequency may be, these frequencies will eliminate the single-phase commutator itself. In this respect the Kando system, now undergoing trials on the Hungarian State Railways, deserves consideration, and according to reports is giving very satisfactory results. Since this system is probably not generally known, a brief description would no doubt be of interest. The supply to the locomotive is high-tension single phase at 50 periods and the drive is by three-phase motors. In order to accomplish this the locomotive carries a phase converter of peculiar construction. It is a single-phase synchronous motor and three-phase generator in one; both machines have a common stator and a common field. The exciter is on the same shaft. The stator carries a single-phase winding covering about two-thirds of the circumference, and a separate three-phase winding covering the whole of the stator circumference. Single-phase energy is taken from the overhead trolley wire, driving the phase converter as a single-phase synchronous motor. The rotating d.c. field system excites also the three-phase generator, which in turn supplies the energy for the three-phase motors. The small exciter is not a constant-

voltage machine, but is arranged for automatic voltage regulation, so that the voltage from the three-phase generator varies approximately as the square root of the motor load, thus ensuring that the motors are working at terminal voltages conducive to maximum efficiency. Simultaneously the alteration of the field values effects a correction of the power factor of the motors, and the overhead trolley system becomes independent of the power factors of the three-phase motors of the locomotives. The single-phase winding can be easily wound for reduced voltages, which will give such currents that the control gear to the motors does not become unwieldy. This presents for single-phase systems a solution much superior to the American split-phase system and, in view of the possibility of using high tension, a serious rival to the d.c. system. Of course, it must be admitted that the d.c. series motor is the traction motor *par excellence*, but it has its drawbacks. There are commutator troubles which can never be separated from d.c. work; the costly conversion in costly rotary substations; and the heavy overhead system owing to the comparatively low transmission voltages. Regarding three-phase traction, the objection appears to be the complexity of the trolley system and the difficulty of speed regulation; in addition, if the national standard of 50 periods is adopted for main-line traction, three-phase motors must have a large diameter and a large number of poles. This objection is overcome by gearing. The objection regarding speed regulation is not so serious as it might appear. Some years ago I was interested in tests with a frequency-changer. This consisted of an ordinary d.c. armature tapped three-phase and supplied with slip-rings. The brushes on the commutator were spaced 120° apart, and the armature worked in an unwound stator. By running the frequency-converter from zero to a maximum speed any desired frequency could be obtained, and by allowing these frequencies to act on the stator of an induction motor any desired speed and an excellent starting torque were obtained. Since then such frequency-converters have been much improved and, by connecting them to the rotor and also allowing correct changes in the voltages, they act simultaneously as phase compensators. The speed regulation discussed was rejected at the time on the argument of complexity of overhead systems with three-phase currents. Yet in Switzerland and Northern Italy three-phase traction has been developed and the authorities concerned appear to have no inclination to depart from their adopted policy. I should like to have the author's views on this point.

Mr. R. A. Thwaites: It is to be regretted that the paper does not give any costs, as costs are all-important in such a scheme as this. The value of the paper would be much increased if the author, in his written reply, would give at least an approximate figure of the cost of energy per unit delivered either to the substations or to the contact wire, together with some indication of the cost per km of track equipment. One of the main objects of this scheme appears to be the reduction in the amount of coal imported, and we in Yorkshire are likely to be seriously affected by any such reduction. The author states on page 894: "From this it can be seen that the electrification of the railways, even if extended to include every line, would result in only a small reduction in the import of fuel into France." But is this quite correct? The amount of coal used by the railways is given as 9 million tonnes, so that if they were all electrified and 90 per cent of the energy were obtained from water power, then France would save something like 8 million tonnes a year. From the figures given in the paper this would appear to be a saving of half the imports of coal into France—a very considerable reduction. Due to the circumstances prevailing, the main transmission lines must follow an almost direct route. It would be interesting to know whether any serious difficulties have been encountered in obtaining wayleaves for these lines, also whether complications are involved every time the line crosses a road, or a telegraph or telephone line.

Mr. H. Parodi (*in reply*): All the sections of the Orléans Company's electrification have been put into service as and when completed. Electric trains have been running for several months between Paris and Étampes and Dourdan, that is to say, over about 60 km of 4-track and 20 km of 2-track route, and the mileage run by the electric trains in this section now exceeds 7 000 km (4 350 miles) per day. For more than a year the city of Orléans has been supplied by means of the 90-kV overhead lines of the Orléans Railway Company from the power stations in the neighbourhood of Paris; and next winter the Eguzon station which was opened in June, 1926, will supply Issoudun, Châteauroux, Orléans and Paris, in addition to the traction substations. Interconnection of the hydro-electric and steam-power stations will thus have been effected, and, in addition, the surplus energy available will be distributed along the above length of railway. Considerable advantages will result from this interconnection of the power stations, for it can easily be proved that it is more economical to transmit between two given points two amounts of energy Q_1 and Q_2 over a single line at a suitable pressure, than over two separate lines at a lower pressure. Considerable advantages from interconnection also will be obtained by the steam stations which will receive energy from the hydro-electric stations in winter when the load on their network is the heaviest, and which will supply with their steam plant electrical energy for the railways in the summer when their load is least. The hydro-electric stations possess ample water storage and will provide a supply of power during those hours of the day which will be most convenient for the steam stations. For example, the Eguzon water-power station can be considered, from the point of view of the Gennevilliers steam station, as an auxiliary supply of 50 000 kW transmitted a distance of 300 km (186 miles). This auxiliary supply will be chiefly used in winter when the demand on the station is greatest, this coinciding with the maximum supply of water.

As regards the relative costs of the steam and hydro-electric supplies, I will merely say that the Union d'Électricité was not neglecting its own interests when it co-operated with the Orléans Railway Company in constructing the Eguzon station.

The installation was designed in the first place by the

Railway Company and subsequently by the General Electric Co. of Schenectady, U.S.A., who supplied the synchronous condensers and the high-tension equipment and gave, through the French Thomson-Houston Co., a full guarantee in regard to the satisfactory working of the complete system. The position and output of the synchronous condensers have been especially approved by some of the distinguished engineers referred to by Mr. A. M. Taylor in the discussion.

The Schoop process has not been employed to coat the Orléans Company's towers, and I do not know why Mr. H. M. Taylor, basing his remarks on incorrect information which is not given in the paper, criticizes a method which has not been employed.

The high-tension lines do not cause any interference with the telephone or the telegraph lines, this immunity being due to the distance apart of the two transmission lines. In carrying out the installation we have complied with the requirement of the Post and Telegraph Administration and the regulations of the Californian Railroad Commission, and in every case it will be found that the new regulations suggested by the Union Internationale des Chemins de Fer have been practically complied with.

It is impossible for me to deal here with comparisons between electric traction and steam traction, such as the energy consumption per kilometre and per tonne-kilometre. These are set out in detail in the articles in the *Revue Générale des Chemins de Fer* mentioned in the paper, and it will be seen that the consumption of electrical energy calculated at the substation busbars corresponds for the same service conditions to a fuel consumption of between 2 and 3 kg (4½ - 6½ lb.) of coal per kilowatt-hour. If, however, a comparison be made—as has very often been done—between actual railway services before and after electrification, but with very different average running speeds, much lower figures will be obtained. As electric traction enables us to obtain a much higher average speed for the same maximum speed as that employed in the steam service, we can run a much more frequent electric service of express trains and goods trains, representing an increase in the carrying capacity of the line. This question is, however, linked up with that of brakes on goods trains, and one may say that it will only be possible to obtain all the advantages of electric traction when we have adopted for such low-speed traffic automatic continuous braking.

As regards the design of the locomotives, the tests which are in progress on the Orléans system will probably show the advantages and disadvantages of the various types suggested, whether individual control of the axles (gearless locomotives with Buchli drive) or group control (locomotives with connecting rods of the "hyperstatic" type introduced by Mr. Kando and of the author's "isostatic" type).

On the question of voltage, it is becoming more and more evident to me that, for the conditions prevailing in Europe, it is desirable to adopt a lower voltage as the density of the traffic increases, whilst for very low traffic density it is essential to employ very high voltages. In the case of metropolitan railways or suburban services there does not appear to be any tendency to give up the use of pressures of 600 or 1 500 volts. Finally, as to the current used, I shall merely state in reply to Mr. French that Italian engineers, after having employed three-phase low-frequency current for the lines of the Northern Railways of Italy, are going to adopt for the Southern Railway electrification three-phase current of the frequency usual for power supply (45 periods). On the other hand, they are going to experiment with direct current at 3 000 volts on the 100-km line from Benevento to Foggia.

For its motor-coach trains the Orléans Company have employed only two methods of connecting the motors, namely, series and series-parallel, instead of three (series, series-parallel and parallel), the sole object being to simplify the control; and I do not know of any metropolitan or suburban railway where the three methods of connection have been used.

Regenerative braking has been used on the high-speed locomotive having fully compensated motors only with a view to obtaining useful information in connection with future electrification of lines having steep gradients.

The rotary converters were connected two in series, because at the time when the matter was under consideration no European or American manufacturer was prepared to build a machine giving 2 000 kW continuously and 6 000 kW for short periods and having 1 500 volts on one commutator. In these circumstances it was much more desirable to connect two 1 000-kW 750-volt machines in series than to have two 1 000-kW 1 500-volt motors in parallel, owing to the much greater reliability and efficiency obtained over high-tension machinery. The Orléans Company have experimented with a 1 000-kW 1 500-volt converter lent by an American manufacturer, but the test has had to be stopped, not on account of unsatisfactory operation but owing to the insufficient output.

With regard to the third rail designed by the author, more than two years' experience has shown that it gives results which are far superior to those obtained with other forms of third rail used on the Orléans Railway, and it has been at the request of the permanent way department that the original pattern of rail has been replaced by the new pattern on the busiest sections of the track. The new rail is of mild steel containing less than 0·3 per cent of manganese and 0·4 per cent of phosphorus; its resistivity is about 7 times that of copper and its breaking strength 36 kg per mm^2 (23 tons per sq. in.), the elongation being 27 per cent.

HIGH-POWER FUSIBLE CUT-OUTS.

By L. C. Grant, Associate Member.

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Summary.

The subject of high-power fusible cut-outs is one entitled to the greatest respect, but it has undoubtedly been neglected in the past. The author has endeavoured to tackle the subject from a logical point of view in the present paper, and, in view of its fundamental importance, the problem of rupturing capacity has been selected as that to which attention is primarily confined.

The paper includes a consideration of the factors influencing the rupturing capacity of a cut-out, and a description of an extensive series of tests carried out on various types of cut-outs, including many of those most widely used to-day. A selection is given from the records of tests on fundamental forms of elementary construction, on plain cut-outs and on various commercial forms, and this shows clearly the inadequacy of such cut-outs for high-power work. Certain recently developed forms of cartridge cut-outs which operated satisfactorily are referred to and their sphere of usefulness is indicated. A description is given of an ironclad oil-immersed cut-out, which appears from the tests to satisfy nearly all requirements for high-power work. A new design of cut-out for small-current high-pressure services is also described.

An attempt has been made, by carrying out actual rupturing-capacity tests, to indicate how far the various types of cut-outs can be safely employed, and a chart has been drawn up to show a comparison between the rupturing capacities of these types.

A striking feature made apparent by the tests is that there are remarkably few efficient cut-outs available. This is all the more to be regretted when it is realized that a fusible cut-out can be made into a most accurate and efficient device—consistency of calibration and consistency of rupturing performance being possible to a high degree of excellence.

Introduction.

Small powers.—Until comparatively recently, fusible cut-outs have been employed only in circuits in which they are called upon to deal with relatively small amounts of power. For such work a plain fusible cut-out (i.e. one in which no special provisions are made to reduce or restrict the operation of rupturing) is often satisfactory. Thus in lighting or industrial power circuits an appropriately-arranged plain fusible cut-out, for example a fuse wire supported on a porcelain carrier in air, will usually suffice to clear a short-circuit with comparative ease. For the worst fault in such a position, amounting probably to 50 kVA at most, the operation will be accompanied by a fair explosion but by employing a somewhat more costly small fusible cut-out of the cartridge type, such a fault can be cleared without any commotion. The author, however, is not at present concerned with this branch of the subject, for, although there are numerous instances where poorly designed fusible cut-outs are in use, there are already available properly damped carrier-type cut-outs and inexpensive low-power cartridge cut-outs which would adequately meet such small-power requirements, as they have met the more difficult conditions described in the present paper.

Larger powers.—The problem with which the present paper is primarily concerned is that of fusible cut-outs capable of dealing with relatively large amounts of power, for which the simple forms of cut-out are entirely unsuitable. The subject may be roughly divided into three main groups, namely, cut-outs for medium- or comparatively heavy-current high-pressure work, cut-outs for heavy-current medium- or low-pressure work, and cut-outs for small-current high-pressure work. The dividing line between the first two groups is difficult to define, and cut-outs which are suitable for one group are also often suitable for the second. These two groups have consequently been dealt with together in the paper. The third group, however, involves quite different considerations and is consequently dealt with separately in the last main section of the paper.

As instances of circuits in which cut-outs in one or other of the first two groups may be used, may be mentioned industrial substations, power-station auxiliary supplies, transmission feeders and distribution networks. Thus it is usual nowadays in power stations to employ an auxiliary transformer bank of the order of 2 000 kVA which could feed perhaps 50 000 kVA into a fault. One important point of difference between a circuit breaker and a fusible cut-out may here be mentioned, in that a properly designed cut-out operates so rapidly that the peak current and the effect of asymmetry must be taken into account in estimating the kVA to be ruptured.

Distribution is carried out largely by means of transformers up to 1 000 kVA capacity. Such transformers are usually fed from a high-pressure system which is capable of maintaining the full potential on the primary of the transformer under almost any conditions. The use of circuit breakers in such conditions entails considerable expense, and if good cut-outs can be used in their stead it will be an unquestionable economy to do so. Such cut-outs must necessarily have a rupturing capacity of 20 or more times the transformer normal capacity.

One point in favour of the use of a cut-out instead of a circuit breaker is that the protection afforded is generally more consistent with the requirements. The characteristics of many distributors, installations and apparatus are essentially thermal, and it is, therefore,

desirable that the circuit-breaking device should also have thermal characteristics. The author has not succeeded in finding for this service any suitable device other than a fusible cut-out, which consistently reproduces a thermal time/current curve.

Scope of the Investigations.

Attention was at first directed to finding out how far existing designs of fusible cut-out were capable of satisfying the various requirements, and also, if possible, to devising improvements in such designs. A lengthy series of tests was carried out, and during these tests changes in design were made with a view to eliminating the troubles which arose.

At the time the investigations were commenced, the author could not find any cut-outs capable of rupturing, with reliability, heavy currents at medium or high pressures, or any reliable cut-outs suitable for small-current high-pressure use. The latter requirement has been satisfactorily met by one of the new designs developed during the investigations, whilst two other new designs appear likely to satisfy the former requirement. A third design gave promising results on heavy-current low- and medium-voltage tests, although further tests have still to be made on this cut-out.

The tests showed that many of the claims made for existing designs of fusible cut-outs could not be substantiated, and the general impression obtained from the tests was that most manufacturers were not correctly visualizing the problem. In the present paper the author has endeavoured to approach the subject from a logical standpoint. Many important problems are involved, but in the limited compass of a single paper it is impossible to deal with all of them. In view of its fundamental importance, however, the problem of rupturing capacity has been selected as the main subject of the paper.

After giving a brief account of the shortcomings of the heavy-pattern plain fusible cut-out, the author has reviewed the various factors affecting rupturing capacity. This is followed by a selection from the records of the tests and a description of the new designs of cut-out evolved, and an attempt has been made to define the limits within which the various types of cut-out may be usefully employed.

Shortcomings of the Heavy-Pattern Plain Fusible Cut-Out.

To obtain a reasonable degree of protection, ordinary copper fuse-wires must be run at a fairly high temperature, which causes deterioration and premature rupturing of the fuse. Hence, between the time a new fuse element is fitted and the time it may operate, the setting is gradually altering. The time/current curve is therefore difficult to control and almost impossible to maintain with consistency. Deterioration also takes place through mechanical vibration, through innumerable changes in temperature due to load variations, air draughts and other causes, and through electrically induced vibration. These factors are fairly well understood and have been dealt with by other investigators.

Factors Affecting Rupturing Capacity of Fusible Cut-Outs.

General.—The term "rupturing capacity" has hitherto been loosely employed, but the author has attempted

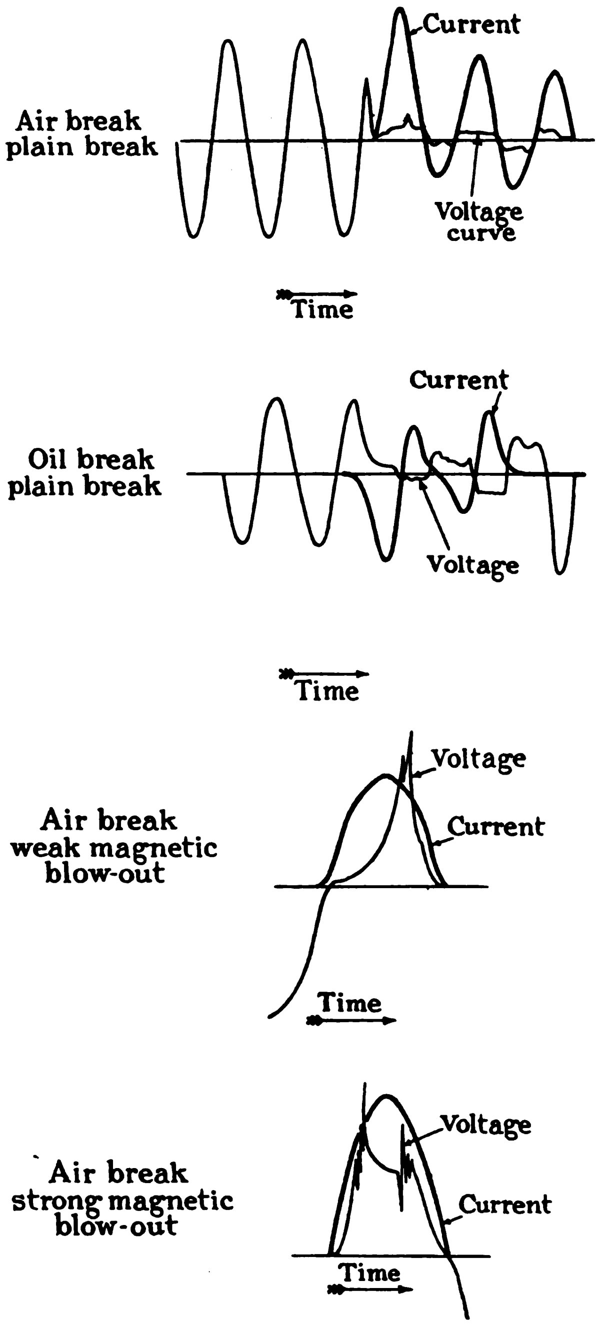

Fig. 1.—Comparison of arc characteristics: (*a*) plain air cut-out, (*b*) oil-immersed cut-out, (*c*) weak magnetic blow-out, (*d*) strong blow-out in air.

to give it a definite significance. Briefly, it may be described as the maximum power which can be safely ruptured by a cut-out. A cut-out may be capable of rupturing large powers, but that alone is not sufficient.

It must clear the fault without a dangerous explosion and without arcing over to neighbouring parts. Thus a plain cut-out of even the most elementary form may be capable of rupturing large powers, but the tests have shown that it cannot be made to do so without a harmful explosion. A more precise definition of rupturing capacity is the maximum kVA which can be cleared by the cut-out without an explosive or other effect which could cause damage to adjacent apparatus.

Magnetic blow-out.—Amongst what might be called external means of assisting the rupturing performance, magnetic blow-out has been extensively employed in various forms. Tests were therefore carried out to determine the value of magnetic blow-out, and it was found that the introduction of proper magnetic blow-out to the arc at the point of rupture has the general effect of decreasing the arcing time but, if misapplied, may produce voltage harmonics. These harmonics have often been found to be of a dangerous amplitude, and the tests indicate that magnetic blow-out may be, and often is, a disadvantage unless intelligently applied. Incorrect form may introduce complex phenomena, resulting in a greater amount of arc energy than in the case of a fusible cut-out not provided with magnetic blow-out. A comparison of arc characteristics to illustrate this point is given in Fig. 1.

If magnetic blow-out be adopted, it should be of simple form. Commercial forms of magnetic blow-out, both for switches and for fusible cut-outs, are far from simple. A common form of magnetic blow-out consists of a horseshoe magnet excited from a coil carrying the main current. The field of such a magnet has several components. There is a simple effect which acts directly upon the arc loop, tending to enlarge it; there is the horizontal field between the cheeks, which tends to move the arc in a straight line, and there are other effects.

The most reliable magnetic blow-out so far tested for heavy-current fusible cut-outs was obtained by bending the main leads at right angles to the fuse element for a few inches, so that there was a tendency for the fuse element to be blown away from the ends of the conductors. This arrangement provides a simple field which keeps the arc away from the contacts and assists materially in the clean extinction of the arc.

With large plain fusible cut-outs, particularly when arranged for magnetic blow-out, there is a tendency for portions of the fusible material to be left in a non-volatilized condition and to be ejected bodily from the carrier. In a number of tests carried out by the author with currents up to 100 000 amperes and employing magnetic blow-out (in some of the tests in the form referred to in the previous paragraph), portions of the fusible elements were blown 300 ft. away.

Oxidation of fusible element.—Unless specially prepared, a copper-wire fusible element will become red-hot at approximately 75 per cent of its minimum fusing current. The temperature at normal full-load current must be below this temperature, and in practice it has been found necessary to limit the continuous full-load current to between one-third and one-half of the minimum fusing current, in order to prevent cumulative oxidation being set up by the heating effect of the normal full-load current.

With certain metals and alloys, the fusible element is liable to oxidize at extremely low temperatures or even under the influence of the atmosphere alone. The oxides can be divided into two classes, namely, those which volatilize at approximately the same temperature as, and those which volatilize at a greater temperature than, the fusible material. When the oxide film breaks down at a temperature near to the fusing temperature of the metal, as with copper, the process of rupturing is not affected to any marked extent by the presence of the oxide; but with metals such as tin, aluminium and zinc the oxides are capable of holding up the molten metal after the current has raised the fusible element to its melting-point.

With open fusible elements of small size the oxidation effect is particularly troublesome. It is found that the oxide skin has the effect not only of increasing the rated minimum fusing current but, what is more troublesome, of exerting upon the fusible element a variable effect which cannot be predetermined.

Powder and similar fillings in cartridge cut-outs.—In cartridge cut-outs it is usually found that oxidation

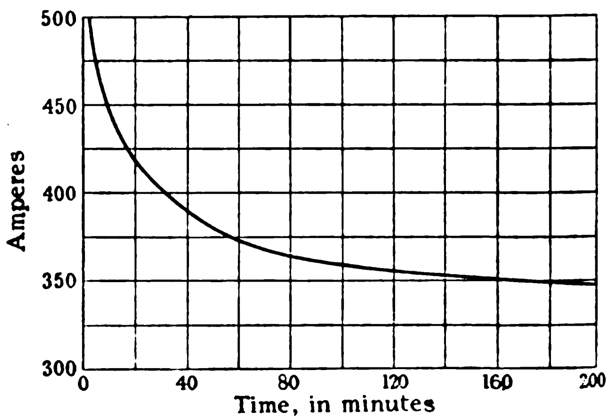

Fig. 2.—Time/current curve of cartridge cut-out with calcium-carbonate compound filling.

troubles are accentuated through the tendency of the filler to support the oxide film. Manufacturers are therefore faced with the alternative of using a loosely packed filling, which avoids to some extent the holding-up action on the fusible element, but introduces a certain amount of oxygen and consequently increases the risk of explosion. A tightly packed filling, although practically eliminating oxygen, supports the fusible element and the oxide film, and the molten material of the fusible element is prevented from being driven into the filler to be cooled.

To be efficient, the filling must be in fairly intimate contact with the fusible element, and, to achieve this, a fine powder is often used. Fine powders pack easily and, assisted by air, heat and moisture, may become solid, which further accentuates the holding-up effect. It will be appreciated that the production of a good filling is no simple matter, there being a sort of Scylla and Charybdis between which a correct course must be steered.

It has been found that a good filling for cartridge cut-outs can be formed by using a calcium-carbonate

base. Calcium carbonate alone is an effective arc damper, but in certain circumstances it is possible for it to assist rather than quell the disruptive agencies, probably through the action of heat on the filler, which results in the production of CO_2. This will tend to extinguish any arcing or burning, but, if produced in excess, will tend to set up a bursting pressure on the container. The introduction of an effective restrainer has been found to be beneficial in controlling this action. Apart from the effect of the CO_2, the action of such a filler seems to be largely a cooling one. On the other hand, it is possible that there is a thermionic effect.

Good results have been obtained with simple inert fillers such as sand, but such a filler introduces other difficult problems, and the best results were obtained from the arrangement described in the previous paragraph. Packing a fusible element affects its characteristic time/current curve, and a curve of a fusible cut-out with calcium-carbonate filling is given in Fig. 2.

Cross-section of fusible element.—The section of the fusible element plays a part in limiting the current on short-circuit, but the effect has been found to be due not so much to the resistance of the element, as is perhaps sometimes supposed, as to the stage in the growth of the short-circuit current at which the element melts.

The element will rupture when the product of watts and time is sufficient to raise the element to its melting temperature. At this point a gaseous gap takes the place of the fusible element and an arc E.M.F. appears. A small fusible element will rupture at an earlier stage in the growth of the current than a large element, and consequently the arc kVA will be less and the duty of the cut-out will be reduced. In other words, it is possible to prevent the current from rising to its full short-circuit value by using a rapidly-acting fusible element.

It is consequently of importance to reduce the amount of metal in the fusible element as far as is possible without introducing risk of oxidation. Expressed in another way, it is desirable to reduce what may be termed the "load/fusing-current ratio," i.e. the ratio of the full-load current to the minimum fusing current. The importance of employing a low load/fusing-current ratio does not appear to be generally recognized in the industry, but an examination of Fig. 3 will show that a low ratio is desirable. In this curve the power ruptured is plotted against the minimum fusing current. The curve is of a general character and embodies the results of a large number of tests on cut-outs of many different types. It is possible to show this effect, perhaps more elegantly, in other ways, but it is doubtful whether it can be shown more strikingly than by the actual test-results embodied in Fig. 3.

The importance of reducing the load/fusing-current ratio is most apparent when the maximum short-circuit power is comparatively heavy. For instance, it has been found by test on a 6 000-volt system with a maximum short-circuit power of 70 000 kVA that a 100-ampere cut-out, if of careless construction, may pass practically the full short-circuit power before it clears. Thus, with a cut-out designed to carry a full-load current of 100 amperes, an examination of the curve will show that with a load/fusing-current ratio of 1 : 2·5 the cut-out will not clear the short-circuit until the power has reached nearly 20 000 kVA, whilst with a load/fusing-current ratio of 1 : 2 it will clear at about 14 000 kVA. With a specially constructed cut-out it is found practicable to reduce the fusing ratio to 1 : 1·2 without introducing oxidation, and it will be

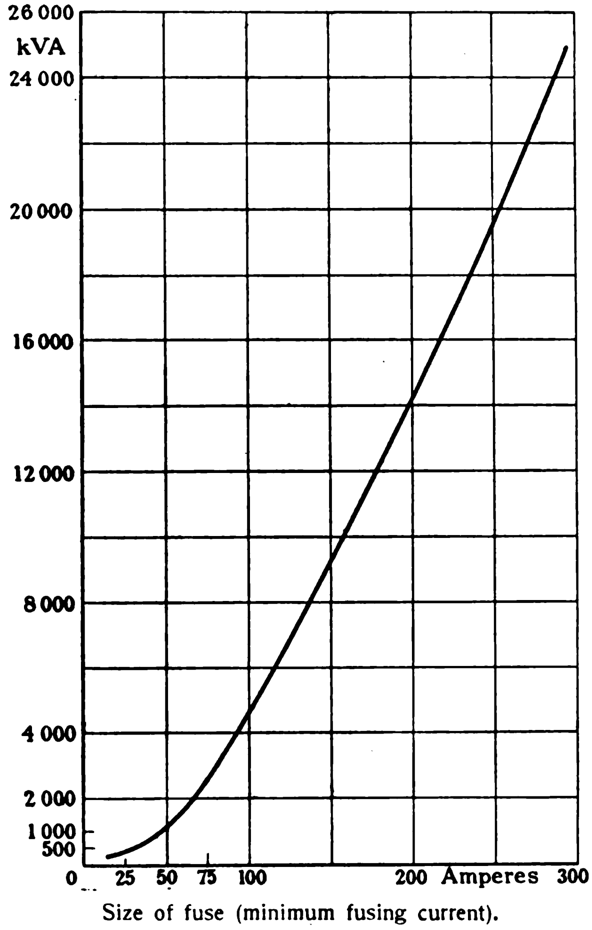

FIG. 3.—Curve showing advantage of reducing "load/fusing-current" ratio.

seen that with such a load/fusing-current ratio the short-circuit power ruptured by the 100-ampere cut-out will be reduced to about 6 000 kVA.

By exercising extreme care in the design of the carrier and by paying attention to factors such as cooling, it is possible to reduce to some slight extent the load/fusing current ratio in a simple form of cut-out, but to obtain the best results it appears to be necessary to make radical changes in the design of the fusible element. Thus in one modern type of fusible cut-out commercially available it is found possible to reduce the load/fusing-current ratio to 1 : 1·2. In this cut-out the functions of melting and heating are separated, and the heat is transmitted to a rupturing point from a calibrated copper neck or restricted portion.

The amount of heat transmitted from the neck is proportional to the load carried by it. When the load reaches a value which causes sufficient heat to be transmitted, the circuit is broken.

Another method is to have a fusible element which will run at a comparatively high temperature, but this introduces other and very difficult problems. Yet another method is described in the next section.

Multiple-element cut-outs.—It has been shown that at the moment of rupture the metallic fusible element becomes a conducting vapour path. It is important to reduce the temperature rapidly in order to reduce the arc energy to the lowest possible value. In cartridge fusible cut-outs the filling cools and condenses the metallic vapour, and the more rapidly the vapour can be driven into the filler, the more rapidly will complete rupture be obtained.

The fusible element should have as small a section and as great a surface area as possible for a given load current, thus giving the filler less work to do and spreading the work over a greater proportion of the filler. Methods of obtaining a small section of the fusible element have been considered in the preceding section. Another method is to employ a subdivided or multiple element or the equivalent, which has the dual advantage of giving a greater surface area in contact with the filler, and of enabling a smaller aggregate section to be used for a given current owing to the increased radiation surface.

It has been shown by Downes that with a five-element cut-out of given capacity the filling will be brought into action twice as rapidly as with the equivalent single-element cut-out. The duration and magnitude of the current will be reduced, with correspondingly lightened duty on the cut-out. The multiple-element arrangement can be formed in various ways. For instance, simple, spaced wire elements, radial strip elements and circumferentially arranged strip elements give equally good results, whilst the corresponding single element gives trouble through explosive rupturing.

Enclosure (general).—It is definitely indicated by the tests that all fusible elements should be enclosed. Many forms of enclosure at present in use are defective. Cartridge cut-outs with weak containers were found to be the rule rather than the exception. Porcelain fuse-carriers are weak mechanically and the porcelain carrier itself is a source of danger. The enclosure of simple fusible elements of the open-arc type in earthed metal, or the enclosure of cut-outs of opposite polarity in a common container, is not a good arrangement, for when clearing any considerable amount of power there is a strong tendency for arcing to be set up to the metal housing and to adjacent poles, and no form of internal insulation so far tested has been found capable of preventing trouble of this nature.

There appear at present to be two satisfactory methods of enclosing fusible cut-outs. One is to make the container of tubular form surrounding the fusible element, as in filled cartridge cut-outs. Such containers are usually located close to the point of rupture and should consequently be of an insulating character. The second method is to immerse the element in oil within a strong metal enclosure. These two methods are dealt with in separate sections.

Enclosures of the insulating type (cartridge cut-outs).—The necessity for employing insulating material for tubular containers limits the choice of materials to a group which includes glass, porcelain, fibre and bakelite, and which have comparatively poor mechanical strength. This is unfortunate, since their proximity to the point of rupture exposes them to high gas pressures, and unless efficient arrangements are made for damping and controlling the explosion set up at rupture, the container is likely to be shattered. When rupturing a power of the order of 30 000 kVA per phase, pressures of the order of 1 000-2 000 lb. per square inch were measured at approximately 1 inch from the point of rupture, and there is reason to believe that higher pressures are set up.

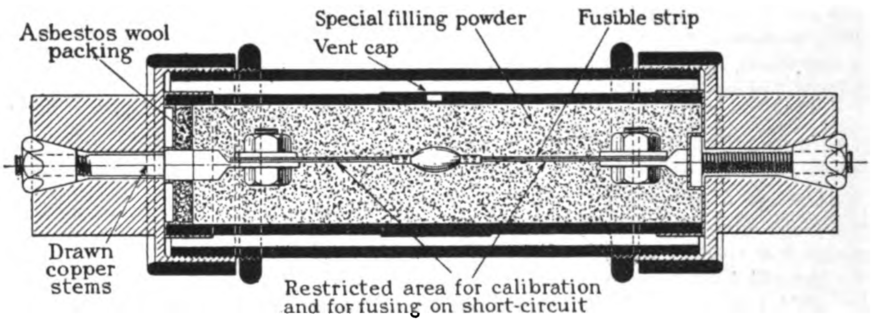

FIG. 4.—Section of filled cartridge cut-out.

Glass and porcelain containers are generally incapable of withstanding anything like this pressure. Bakelite and fibre containers can withstand considerably more pressure than glass containers of similar form, but the enclosure of a plain element in such a container with only air or a liquid does not provide a safe arrangement, since the pressures set up under such conditions are often more than the container can withstand. The tests have not brought to light any substance of liquid form which appreciably reduces the pressure set up at the moment of rupture.

Even with powder-filled cartridge cut-outs high pressures are set up which render glass and porcelain tubes of the usual dimensions unsuitable as the material for the container. Common fibre also is unsuitable, partly

because (although much more tenacious than glass) it is not strong enough to meet the requirements of high-power work, and partly because it is hygroscopic. The latter is a serious drawback, for damp will tend to make the container conductive and will also distort it and cause rapid deterioration, besides reacting harmfully on the filling.

Bakelite has been extensively used for the containers of cartridge cut-outs. It is better mechanically than the materials just mentioned and is almost non-hygroscopic. The chief troubles are the non-uniformity of batches and the conductivity along the laminæ, and it is also somewhat expensive. A combination consisting of a glass external tube and a fibre or bakelite internal tube is also being used. A special form of bakelized fibre has been found to give the best all-round results.

Table 1 shows the results of an absorption test on a number of materials, all of which are capable of standing

TABLE 1.

Absorption Test after 7 Days' Immersion.

Material	Percentage increase in weight
Red fibre	39·1
Grey fibre	36·0
Bakelized grey fibre	8·9
Commercial bakelized paper tube ..	30·0
Moulded bakelite tube	1·2
Bakelized fibre tube *	0·05

* After 65 hours, this material withstood a pressure of 3 400 lb. per sq. in.

up to the temperature of the molten fuse elements without damage.

Another important point is the fixing of end caps in cartridge cut-outs, for it is difficult to arrange fibre, bakelite, and similar substances in the form of a closed container. One common arrangement is to pin a screw-threaded brass ferrule to each end of the tube and to screw brass ends and contacts on to the ferrules. With this arrangement the pin fixing is liable to tear out. Another common method is to cut a screw-thread on each end of the tube and to screw the end caps directly on to the tube. In this case the thread is liable to strip. Yet another way is to screw a brass ferrule directly on to the tube and to screw the cap and contact on to the ferrule, but even this arrangement appears to be incapable of withstanding the forces which the tube itself can stand.

An arrangement which proved satisfactory in the tests is illustrated in Fig. 5. This consists of two brass ferrules screwed respectively into the inside and on the outside of the tube, thus clamping the tube between the two ferrules, the end cap being screwed on to the exterior of the outer ferrule.

Enclosure in metal with oil immersion.—The enclosure of fusible elements in metal containers without damping substances has been found to be unsuitable, chiefly because of the unrestricted range of the arc and the explosive effect which results in destruction of the carrier and arcing to the framework. When the fusible element is immersed in oil the arc is restricted to a comparatively small space, but the pressures set up are not reduced; rather are they augmented. This necessitates a strong housing.

To avoid flash-over and creepage over the internal and external insulation, the dimensions of the housing must be greater than with cut-outs of the insulating container type. In the development of metal-enclosed fusible cut-outs with oil immersion, the dimensions of the parts have approximated to those usual for oil switches. This may increase the cost, but it results in apparatus having a rupturing capacity intrinsically higher than in cut-outs of the insulated container type. A fusible cut-out of this pattern must be capable of withstanding explosion pressures of the order of hundreds of pounds per square inch. In tests carried out on a 6 000-volt three-phase pattern when rupturing approximately 50 000 kVA, pressures of the order of 600 lb.

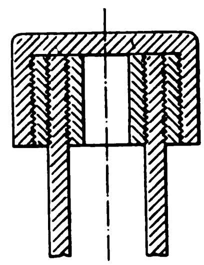

FIG. 5.—Arrangement of end-cap for cartridge cut-out.

per square inch have been measured within 2 inches of the arc, and pressures up to 200 lb. per square inch at the walls of the container.

RUPTURING-CAPACITY TESTS ON SIMPLE FORMS OF CUT-OUT.

Introductory remarks.—If a plain fusible cut-out in air operates under overload conditions, the element melts comparatively slowly, an arc is established and burning vapour is produced. If it operates on short-circuit, the effect is explosive and, in addition to the scattering of hot metal and the heat of the arc, damage is often caused to the carrier and other parts of the cut-out. There is consequently a considerable risk of personal injuries, and the psychological effect on operators is a factor to be considered. Indeed, it may be said that we have now reached the stage when uncontrolled power arcs are inadmissible. They have already been largely eliminated in switchgear by the development of oil-immersed switches, but comparatively little has been done in this direction with fusible cut-outs, and a cut-out which can be relied upon to operate satisfactorily without risk of a dangerous explosion is a recent innovation. Most of the cut-outs at present on the market are defective in this respect.

The present section of the paper gives an account of the tests carried out on plain cut-outs in air and on various commercial forms of cartridge cut-outs, assisted air cut-outs and liquid-filled tubular cut-outs.

Tests on fundamental form of fusible cut-out.—With a plain cut-out consisting of a fusible element mounted in

a carrier in air, an arc is set up at the moment of rupture, with nothing material to assist in its breakdown. There is no essential difference between this and the fundamentally simple arrangement consisting only of a piece of wire stretched between terminals. Indeed it could even be maintained that this fundamental form, as far as its circuit-breaking properties are concerned, is the better arrangement and, moreover, there is not the risk of splintering of the carrier, which is generally formed of a comparatively fragile substance.

Tests were carried out on this fundamental form arranged as in Fig. 6 and it was shown that it will clear short-circuits every time, provided the gap is large enough. On 6 000 volts a 12-inch gap is not sufficient, but moderate results are obtained with a 24-inch gap, whilst with an increased gap the circuit

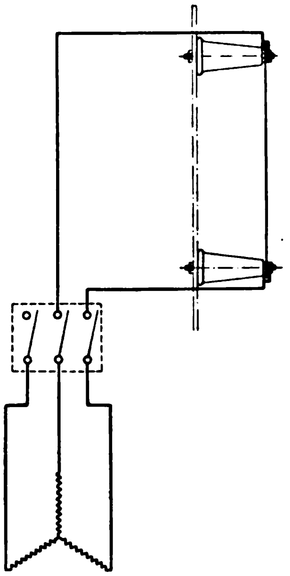

FIG. 6.—Arrangement of fundamental form of fusible cut-out as tested at 6 000 volts.

was cleared every time. Corresponding tests were carried out at and below 440 volts. The important point shown by these tests is that the process of rupturing with such a cut-out is not materially different from that with any of the undamped forms of cut-out, for a tremendous and destructive explosion took place.

Let us consider a specific instance, that of a cut-out connected to a source capable of giving a short-circuit power of the order of 50 000 kVA at 440 volts, a likely condition as was pointed out in an earlier section of the paper. Some engineers would be horrified at the idea of using this fundamental form of cut-out in such circumstances. Others would put the same wire into a porcelain or other carrier—an addition of questionable merit—and would then consider for some obscure reason that conditions were entirely different. Others, whilst neglecting the fundamental insecurity of the arrangement, would go to the trouble of specifying the dimensions of the carrier and the confining case, the size of the contacts and other factors, which from a rupturing-capacity point of view are irrelevant.

The problem must be attacked in a more logical way by investigating the prime causes of the trouble. The rupturing of the circuit produces a certain amount of thermal energy in an explosive manner, and the immediate result is the production of an arc and the explosion of a quantity of vapour. The problem can be solved only by reducing the arc energy and controlling the explosive effect; but efforts to do this with simple fusing arrangements have been unsuccessful, as the tests described below in this section will show. If these effects can be controlled and, in addition, the whole of the disruptive phenomena isolated, for instance by complete enclosure, there should be no external evidence that the internal conditions are undergoing any change even during the rupturing process. Many engineers with experience of heavy-duty fusible cut-outs will doubtless regard this as an ideal which is difficult, if not impossible, to realize. This is true when considering a cut-out in air, whether it be built into a carrier or placed in an iron box or arranged in any of the well-known ways, and it is also true of other well-known simple forms of cut-out, and of many commercial cartridge cut-outs, but entirely different results can be obtained with well-designed cut-outs, as will be clearly shown in later sections of the paper.

Tests on heavy-duty plain cut-out.—The performance of a heavy-duty plain cut-out on short-circuit is described below in some detail in an attempt to present a picture of the performance of the majority of power cut-outs of this type. The tests were a reproduction of the conditions obtaining with the auxiliary supply in a modern power station, and were similar to the conditions to be found to-day on many alternating-current distribution systems.

The cut-out consisted of three separate carriers for three-phase working, with porcelain-shrouded contacts and insulating barriers between phases and to earth. The elements were rated at 200 amperes continuous carrying capacity. The general construction was heavy, the weight of the unit being about 100 lb. As will be seen, the results were disastrous, there being a huge flash and report accompanied by flying fragments, and it is almost certain that any person or apparatus in the neighbourhood would have been badly damaged.

A three-phase transformer bank consisting of two 1 200-kVA transformers in parallel was coupled to a 6 000-kVA three-phase 40-cycle 6 600-volt turbo-alternator capable of giving a maximum of 70 000 kVA on dead short-circuit. The tests were commenced with a pressure on the transformer secondaries of 180 volts between phases, as shown in the oscillogram (Fig. 7). On short-circuit at full voltage the transformer bank was capable of giving a maximum current of about 100 000 amperes (peak). The instantaneous current value actually attained was 8 446 amperes.

In this test, the sequence of events was as follows: All connections were made and current was switched on from the high-pressure side. Before the current had reached its first peak, the elements ruptured with a loud report. Simultaneously, there was a blinding flash, apparently several feet across and lasting no longer than 1/80 second. One-thirtieth of a second after the flash, a cloud of gas 2 ft. in diameter had gathered, having been

forcibly ejected from the bodies of the fuse carriers. One-fifth of a second from the start, molten material was first noticed being ejected, and this lasted altogether for $\frac{1}{8}$ second, at the end of which time the molten material had succeeded in kindling a fire amongst a with the usual intolerable explosion, with flame and burning fragments ejected in all directions, but cleared the fault. At the sixth short-circuit (at 440 volts) a second flash-over between phases took place, with results similar to those of the first test.

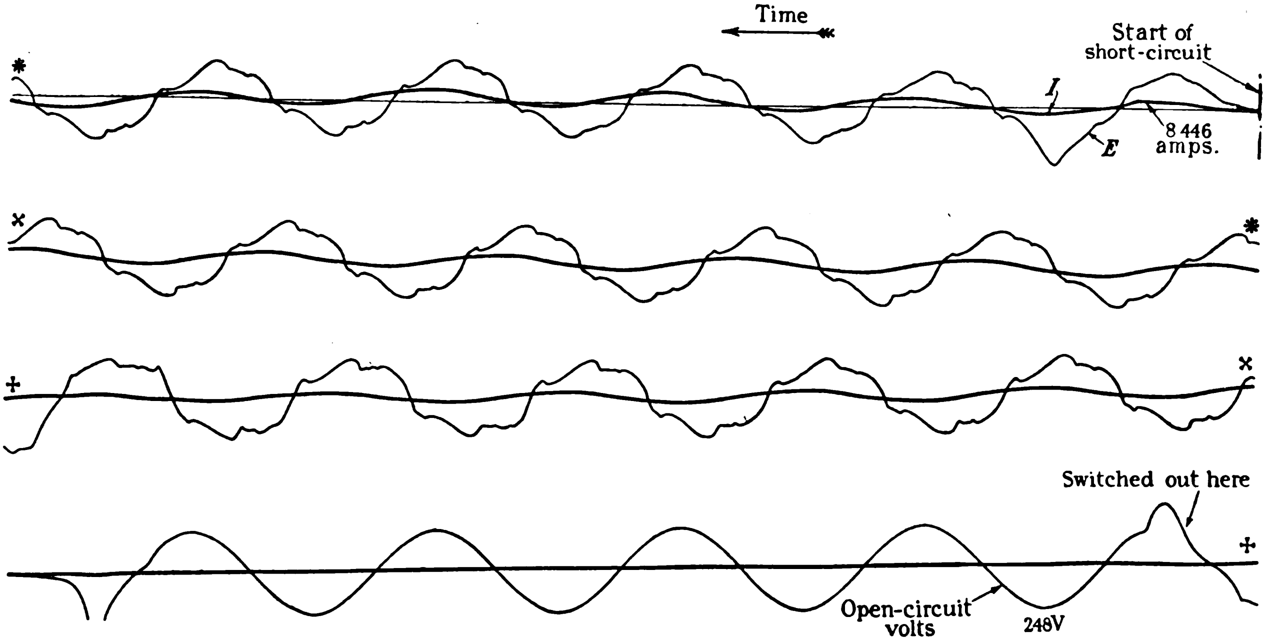

FIG. 7.—Short-circuit test at 180 volts on heavy-duty plain cut-out.

handful of waste on the ground about 3 ft. below the fuse chamber. At $\frac{1}{8}$ second from the start, the smoke and gas cloud was 4 ft. across, and at $\frac{1}{3}$ second, it was 12 to 15 ft. across. The cloud was very dense and came from all sides of the apparatus. It was found on

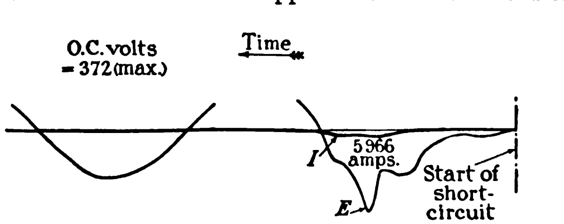

FIG. 8.—Short-circuit test at 265 volts on plain cut-out.

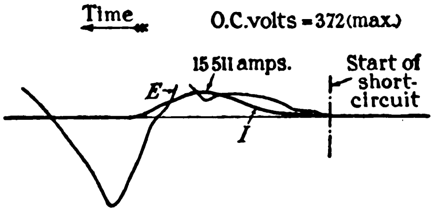

FIG. 9.—Short-circuit test on plain cut-out; voltage = 265.

dismantling the apparatus that there had been an arc-over between phases due to the hot gases given off by the molten fuse elements. Altogether a total of about 1 cubic inch was burnt off the connections in this way.

In four subsequent tests at voltages ranging from 150 to 440 volts between phases, the cut-outs operated

There were two failures out of six tests (oscillograms of four of the five remaining tests are shown in Figs. 8, 9, 10 and 11, of which Fig. 11 shows the sixth test), the better results on the second to fifth tests possibly

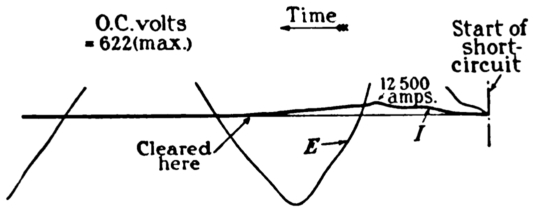

FIG. 10.—Short-circuit test at 440 volts on plain cut-out.

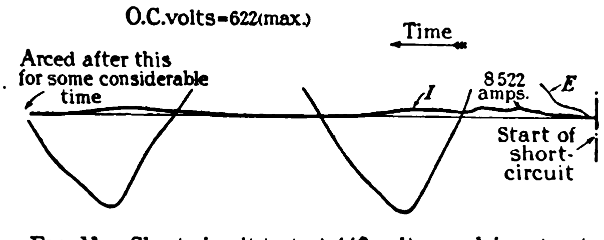

FIG. 11.—Short-circuit test at 440 volts on plain cut-out.

being due to the increased clearance through burning in the first test, but more probably the tests represent a normal average of breakdowns.

These and similar tests serve to show that plain cut-outs, however carefully designed, are inadequate on heavy-duty work and are dangerous alike to the operators

and to all apparatus associated with them. Cinema records in addition to oscillograph records were taken of these tests and also of the comparative tests described in the next sub-section.

Tests on commercial tubular cut-outs.—Similar tests were carried out on many commercial types of tubular cut-outs with liquid, powder and other fillings and at various voltage ratings. The majority of these tests were extremely disappointing and even disquieting; the cut-outs were frequently destroyed, resulting in an open arc between the main contacts. A brief description of a representative selection of these tests is given below. The first group was carried out on low- and medium-pressure cut-outs (500 volts and under), the circuit arrangements being similar to those described for the heavy-duty plain cut-out referred to in the previous sub-section, whilst in the remaining nine tests the high-pressure cut-outs were connected directly across the machine terminals. Oscillograph records of some of these tests are illustrated in the paper, the figure numbers being given in brackets. Many of these tests were carried out at reduced voltage, but this made little or no improvement in the performance.

Test at 350 volts, 40 cycles, on 250-ampere filled cartridge cut-out with zinc element in fibre case: blew to pieces, big flash and report, some smoke.

Test at 350 volts, 35 cycles, on 250-ampere cartridge cut-out in fibre case: blew to pieces, large flash, loud report.

Test at 350 volts, 40 cycles, on 250-ampere aluminium-element cartridge cut-out: blew out at top end cap, rupturing the metal part, cloud of smoke and explosion.

Test at 440 volts, 40 cycles, on 300-ampere pebble-filled cartridge cut-out for network use, zinc element: orange flame, loud explosion, blew to pieces (Fig. 12).

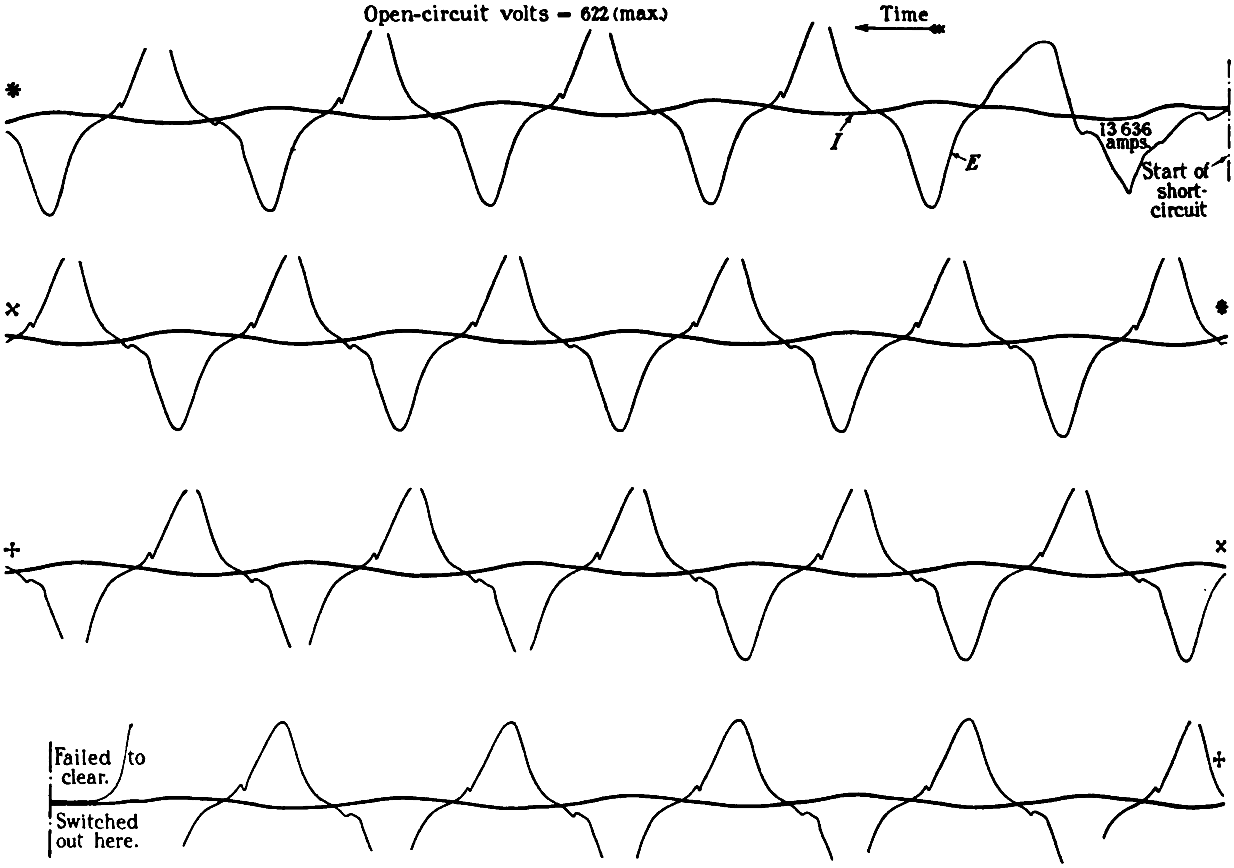

FIG. 12.—Short-circuit test at 440 volts on 300-ampere 500-volt commercial cartridge cut-out.

Test at 350 volts, 40 cycles, on zinc-element inert dust-filled cartridge cut-out rated at 500 volts, 150 amperes: flame blew out at top, fairly loud noise, smoke: noise heard after cartridge had blown, indicating that it had not cleared (Fig. 13).

Test at 250 volts, 40 cycles, on 200-ampere early-pattern cartridge cut-out with unknown filling: end piece blown several yards away, big flash, loud report and smoke (Fig. 14).

Test at 350 volts, 40 cycles, on enclosed 250-ampere cartridge cut-out: flame and a lot of smoke, not much noise, jaws of top contacts burnt (Fig. 15).

Test at 350 volts, 40 cycles, on 250-ampere pebble-filled cartridge cut-out: blew to pieces, big flash, loud report.

Test at 350 volts, 40 cycles, on 250-ampere chalk-filled cartridge cut-out: blew out at top, grey smoke, no flash.

Test at 4 500 volts, 40 cycles, on glass-tube cut-out filled with extinguishing liquid, peak current 4 500 amperes: bottom contact sheared due to force of explosion, fuse cleared (Fig. 16).

Test at 5 000 volts, 60 cycles, on pressure-chamber cut-out: blew to pieces with loud report, smoke, flying fragments.

Test at 6 030 volts, 40 cycles, on 20 000-volt glass-tube cut-out, current 4 800 amperes: failed to clear and arced until cleared by main circuit breaker.

Test at 6 000 volts, 40 cycles, on 11 000-volt bakelite-tube cut-out filled with extinguishing liquid: tube burst and arc set up in air across terminals, circuit cleared by oil switch, current in first half-cycle 7 500 amperes (Fig. 17).

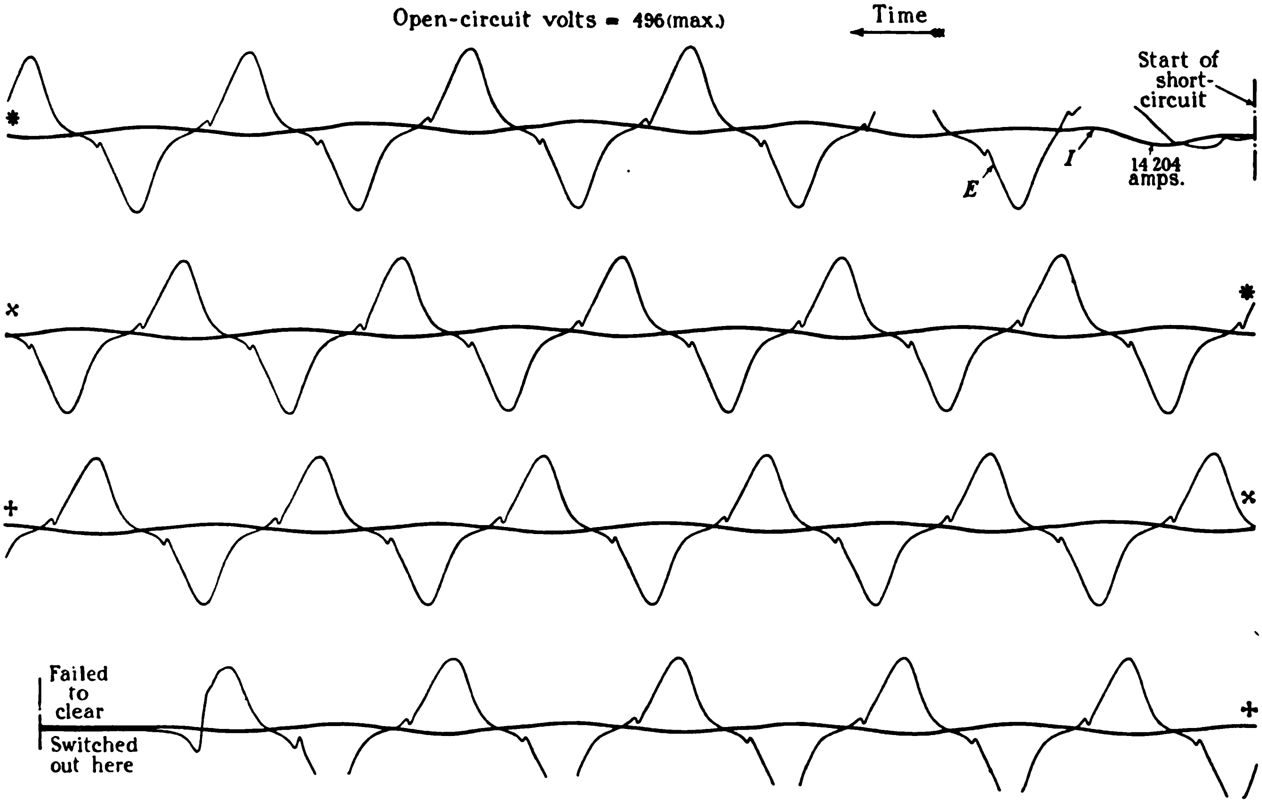

FIG. 13.—Short-circuit test at 350 volts on 150-ampere 500-volt commercial cartridge cut-out.

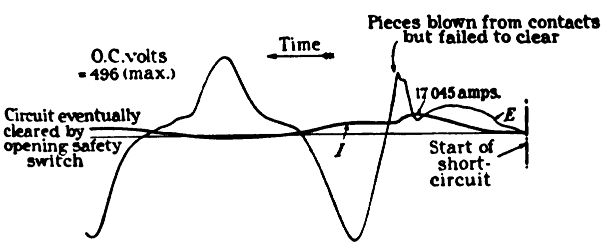

FIG. 14.—Short-circuit test at 350 volts on 200-ampere old-pattern 500-volt cartridge cut-out.

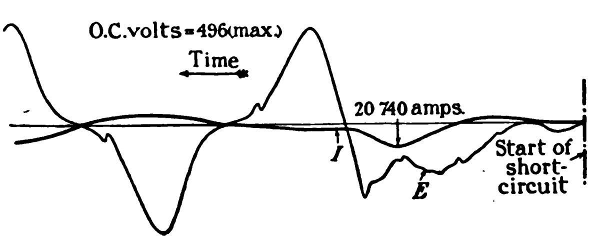

FIG. 15.—Short-circuit test at 350 volts on 250-ampere commercial 500-volt cartridge cut-out.

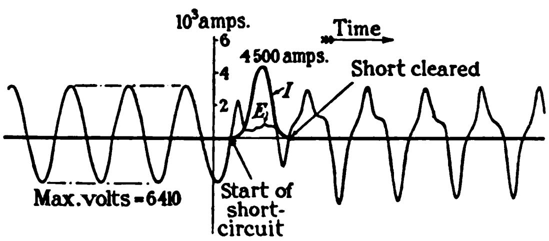

FIG. 16.—Short-circuit test at 4 500 volts on 6 000-volt 25-ampere liquid-filled glass-tube cut-out.

Test at 6 000 volts, 40 cycles, on 11 000-volt glass-tube cut-out with extinguishing liquid: cut-out blew to pieces with bad flash and explosion, but cleared short-circuit (Fig. 18).

Test at 4 000 volts, 50 cycles, on "expulsion" cut out: bad explosion, smoke (Fig. 19).

Test at 5 500 volts, 50 cycles, on " expulsion " cut-out: blew to pieces with loud report; smoke, flash and fragments, portions of fuse carrier picked up 300 ft. away.

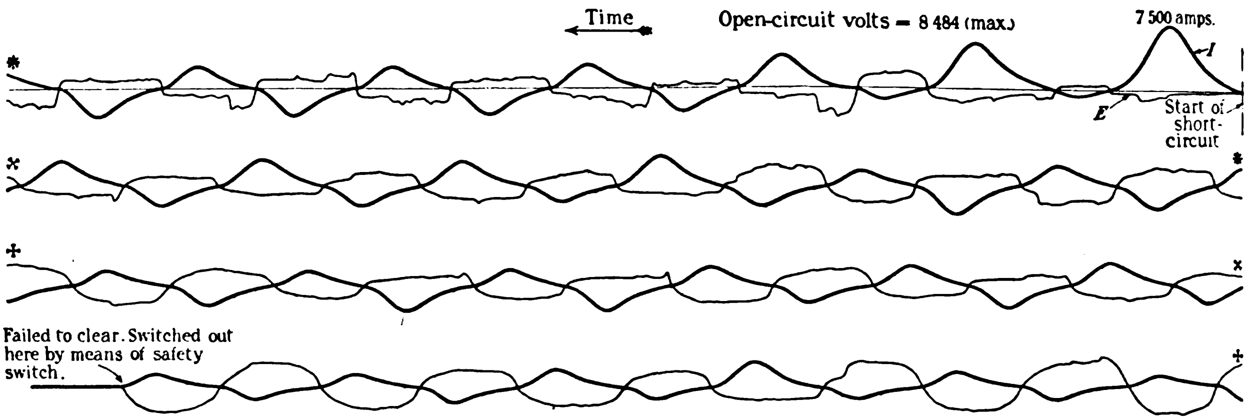

FIG. 17.—Short-circuit test at 6 000 volts on 11 000-volt 20-ampere bakelite-tube cut-out.

Test at 3 300 volts, 40 cycles, on 3 300-volt foreign oil-pot cut-out: half of oil ejected, interior found to be broken up after test; fuse arced for a prolonged period (Fig. 20).

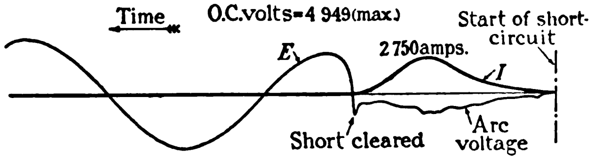

FIG. 18.—Short-circuit test at 6 000 volts on 11 000-volt 20-ampere glass-tube cut-out.

Test at 3 300 volts, 40 cycles, on 3 300-volt oil-pot cut-out: oil, smoke and flame ejected, flashed over to earth internally (Fig. 21).

MODERN TYPES OF FILLED CARTRIDGE CUT-OUTS WITH SPECIAL FILLINGS.

It was found on test that certain recently developed types of cartridge cut-out give a performance entirely different from that of the older types referred to in the last section. They have been tested for low-pressure work and for high-pressure work (up to 6 000 volts) with equally good results.

One design has already been referred to and is illustrated in Fig. 4. It consists of a robust cartridge cut-out with a bakelized fibre container and strong metal ends. For extra-heavy duty a double container is used (as shown in the figure) with a vent arrangement between the inner and outer containers. It is a difficult matter to arrange an effective vent which will operate sufficiently rapidly to relieve the sudden rise of gas pressure. In the present instance a thin paper seal across a hole of predetermined dimensions has proved to be quite effective. The fusible element was evolved after considerable trial and, apart from its rupturing-capacity performance, the calibration for load conditions was found to be exceptionally accurate. The filling, which

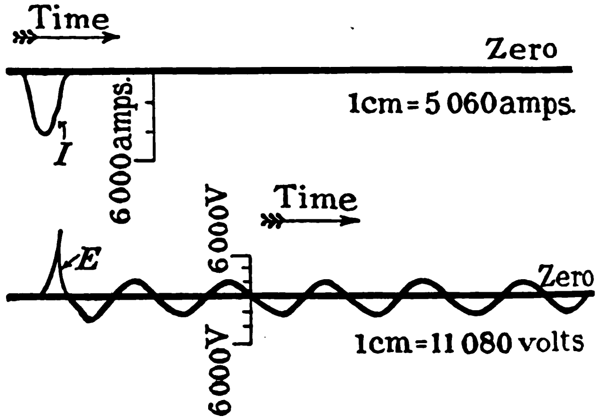

FIG. 19.—Short-circuit test at 4 000 volts on 11 000-volt 25-ampere expulsion cut-out.

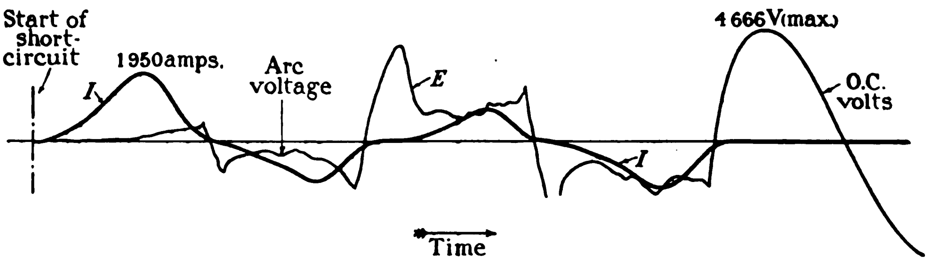

FIG. 20.—Short-circuit test at 3 300 volts on 3 300-volt 25-ampere oil-pot cut-out.

has calcium carbonate as a basis, was also determined by experiment.

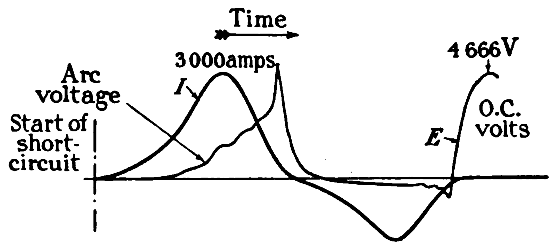

FIG. 21.—Short-circuit test at 3 300 volts on 3 300-volt 25-ampere oil-pot cut-out.

In tests similar to those described in the previous section, which resulted in the destruction of plain cut-outs and commercial tubular cut-outs, the present section, and although the fault current was carried for only a small fraction of a second, there was yet sufficient time to allow the rubber to liquefy and to run out at the ends of the cable, accompanied by clouds of smoke.

Another modern type of cartridge cut-out was also subjected to tests. It had a moulded container of ceramic material and a simple inert filler of clean sand. This cut-out was not so exhaustively tested as those previously referred to, but in medium-pressure tests (up to 440 volts) it was proved to be capable of standing up to short-circuits of considerable magnitude. A characteristic oscillogram for this cut-out is shown in Fig. 24.

The Ironclad Oil-Immersed Cut-Out.

Preliminary remarks.—The ironclad oil-immersed fusible cut-out is a recent development. One of the first difficulties to be surmounted was that of the heating

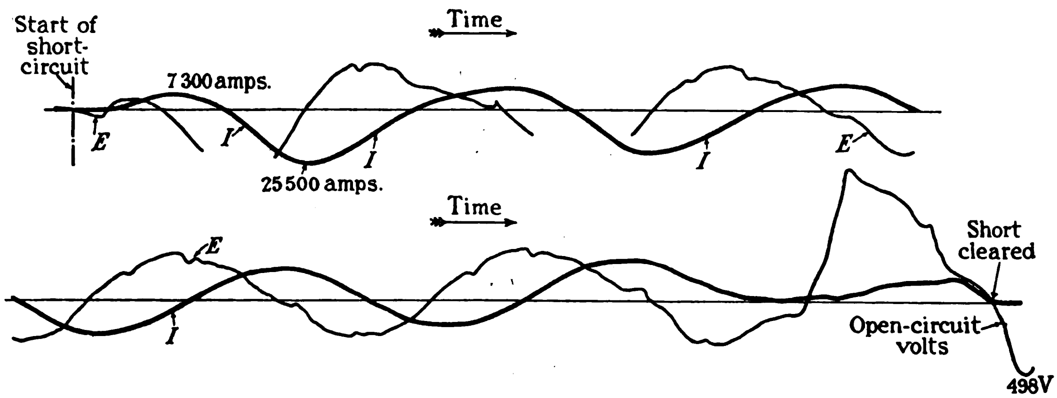

FIG. 22.—Short-circuit test at 350 volts on 500-volt 400-ampere modern, filled, cartridge cut-out.

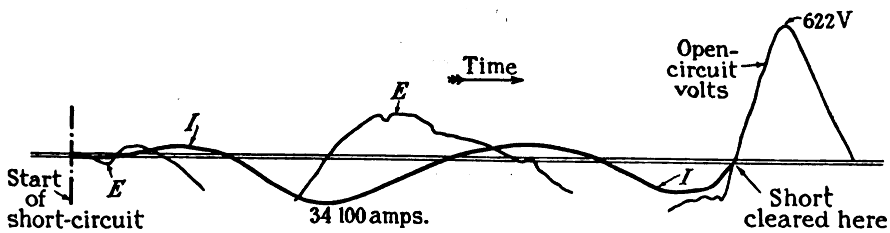

FIG. 23.—Short-circuit test at 440 volts on 500-volt 400-ampere modern, filled, cartridge cut-out.

cut-out cleared the short-circuit satisfactorily with no sign of flash or flame and with no report. Characteristic oscillograms of medium-pressure tests are given in Figs. 22 and 23, equally good results being obtained in the high-pressure tests.

It was perfectly safe to be in the vicinity when this cut-out was opening a "potential short-circuit" of 100 000 amperes. (The term "potential short-circuit" is used to indicate the maximum current which could be fed into a dead short-circuit if there were only the inherent reactance of the system to limit the current; since the fuse exerts a limiting effect, the actual short-circuit current is usually considerably less than the potential short-circuit current.) The only sign of anything happening was the melting of the insulation of the connecting cables, which took place in every test irrespective of the type of cut-out under test. The cables were of approximately 0·25 square inch of the fusible element. This has caused trouble in the past and is one of the reasons why the design has not

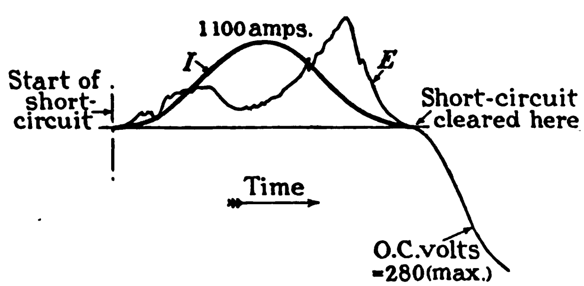

FIG. 24.—Short-circuit test on 500-volt reinforced-container cartridge cut-out with inert filler.

been developed before. In earlier papers on the subject, it is stated that oil-immersed fusible elements must be

run with a large voltage-drop on account of the high current density. It is stated that in such conditions the oil gets hot and that no cut-out should be allowed in which the fuse wire is in contact with or immersed in oil.

With long fuse wires the heating effect is certainly sufficient to raise the oil to a dangerous temperature.

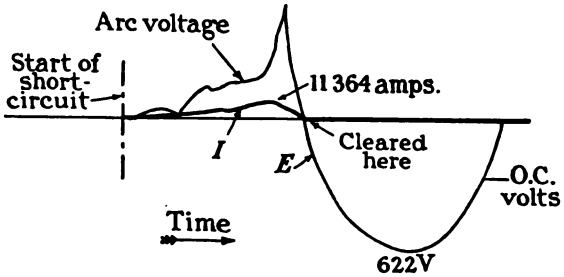

FIG. 25.—Short-circuit test at 440 volts on 440-volt oil-immersed ironclad cut-out.

Length of element and current density are responsible for the energy loss and consequent heating of the oil. Experiments were made to determine whether a reduction in the dissipation of energy could be obtained by considerably shortening the fusible element. As a result, a satisfactory fixed break was evolved for low-pressure work, but for high-pressure work it was found desirable to employ springs to ensure a rapid and long break.

Low- and medium-pressure type.—A number of tests similar to those described in previous sections were carried out on a 600-volt three-phase 200-ampere ironclad oil-immersed cut-out. The three phases were mounted within 2 inches of one another and at a similar distance from the iron case, which was earthed. This cut-out broke, without any sign of operation other than the ejection of a slight spray of oil through a somewhat faulty flange, short-circuits similar to those which destroyed the other types of cut-out. Similar tests on other sizes showed equally satisfactory results. A characteristic oscillogram is given in Fig. 25 for a 440-volt cut-out, and a typical 440-volt installation is shown in Fig. 26.

High-pressure type.—Fig. 27 shows a sectional view of a 6 600-volt oil-immersed cut-out, and Fig. 28 illustrates a typical complete installation. The general construction will be clear from the figures. A large oil volume is provided, primarily for the purpose of keeping up the rupturing capacity and of assisting the cooling process. In reducing the fuse length, a limit is reached when the end connections exert an appreciable effect on the cooling of the fuse wire. A length of $1\frac{1}{2}$ inches was finally adopted. It is true that a certain amount of cooling is exercised by the contacts on a fuse wire of this length, but the effect is consistent and good calibration is possible. As has been mentioned, springs are used to give a long break, and tests were carried out to determine the maximum arcing distance. Finally, the contacts were so arranged that in breaking a 50 000-kVA short-circuit on pressures up to 6 600 volts, the distance between the contacts was about four times the maximum arcing distance.

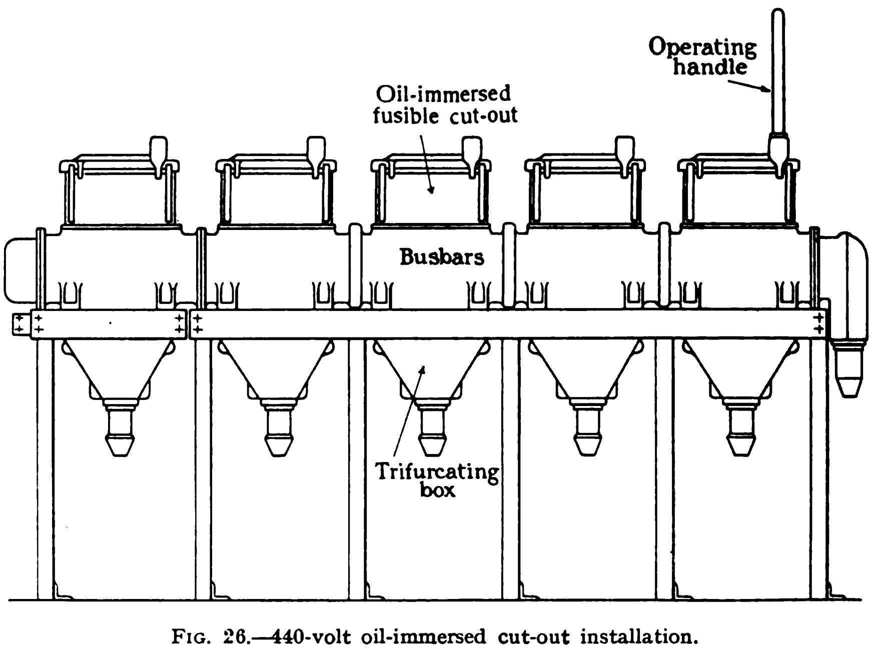

FIG. 26.—440-volt oil-immersed cut-out installation.

The arrangement of springs was also determined by experiment. The normal speed of break in oil-immersed circuit breakers is about 5 ft. per second, and the maximum speed used is from 12 to 15 ft. per second. This is generally considered to be the maximum safe speed. Increased speeds were, however, tested with the object of extinguishing the arc within the first half cycle, which has been shown by test to reduce the shock to plant, mains, etc., to a remarkable extent.

The noise and shock due to plant when subject to short-circuit are well-known, but by the use of fuses with their characteristic quick clearance this noise can be

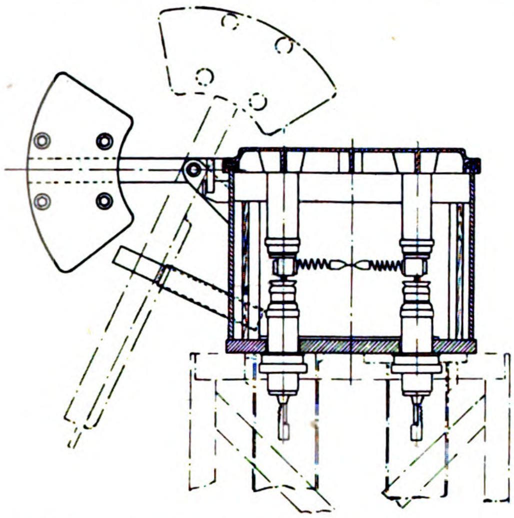

FIG. 27.—Section of oil-immersed fusible cut-out.

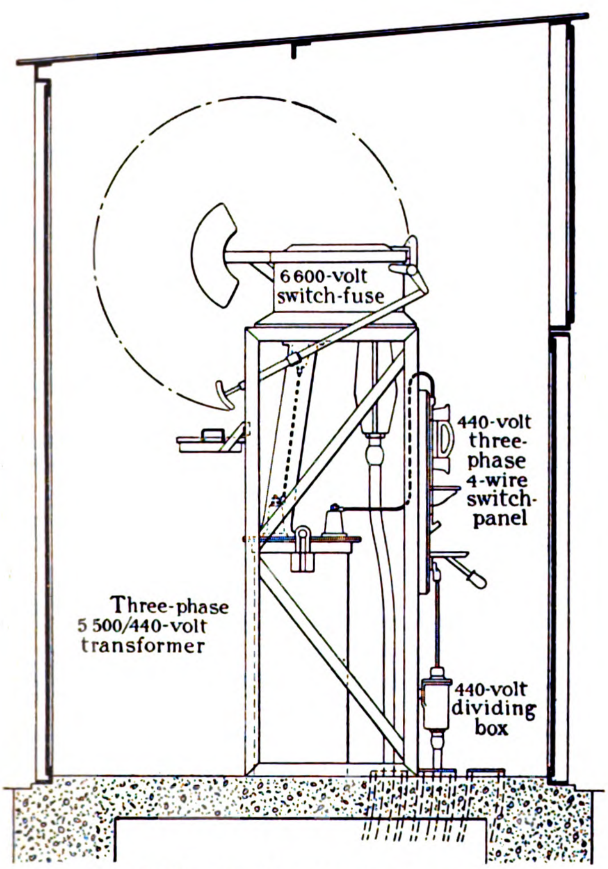

FIG. 28.—6 600-volt oil-immersed cut-out installation.

reduced to a mere click, which is frequently barely discernible. It was found that the increased speed necessitated a speed of break of 30 ft. per second, and the spring arrangement was finally arranged to give 40 ft. per second. This represents the maximum safe speed of break which can be employed (at any rate for work of the class being dealt with) without introducing the risk of pressure-rises through enforced decay of the current—an important point. It is of the utmost importance that the speed of break should not be too high or else the arc will be lengthened too rapidly, a condition analogous to introducing resistance into the circuit, with the aforementioned risk of pressure-rise.

Oxidation troubles.—After oil cut-outs of this pattern had been in service for some time, it was found that an action was taking place on the fusible elements, which gradually became covered with a brown deposit,

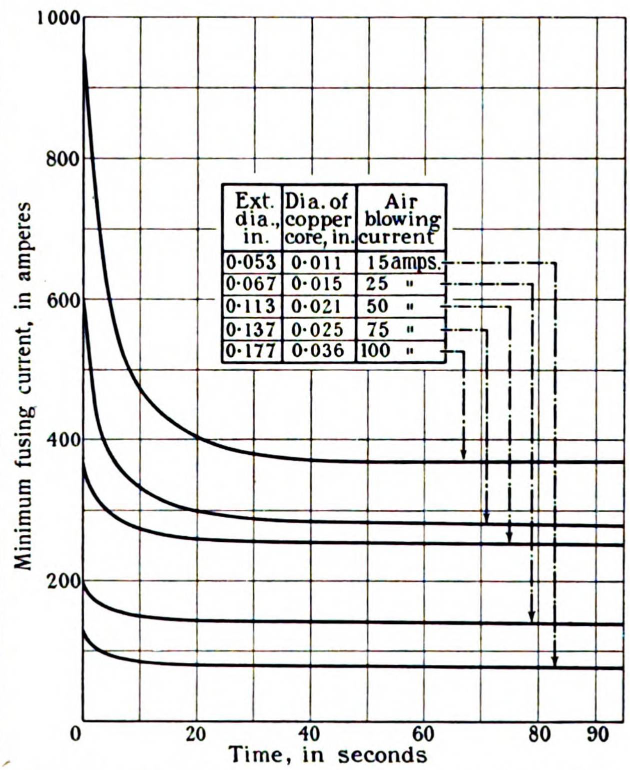

FIG. 29.—Time/current curves of oil-immersed bi-metallic fusible elements.

and the metallic portion appeared to be reduced in section cumulatively, until finally the element would melt on reduced current or even spontaneously. This appeared to be a recrudescence in a new form of the old oxidation trouble experienced with air cut-outs, and in oil the trouble was experienced with any load/fusing-current ratio lower than 1 to 3. In order to avoid this trouble, it was found necessary to adopt a load/fusing-current ratio of 1 to 6, which, of course, gives indifferent protection.

It was believed that the action was at least partly catalytic, but from the very mechanism of the action it was clear that catalytic action was not alone responsible. When copper wires were used, it was found impossible to overcome the trouble while retaining a reasonable load/fusing-current ratio, and bi-metallic

fusible elements having a copper core sheathed with tin or tin-lead were finally adopted. The cumulative deterioration process was thus eliminated, apparently due to the provision of increased radiation surface for a given current density, with consequent reduction of the surface temperature, and perhaps also to the substitution of a comparatively inert agent for copper.

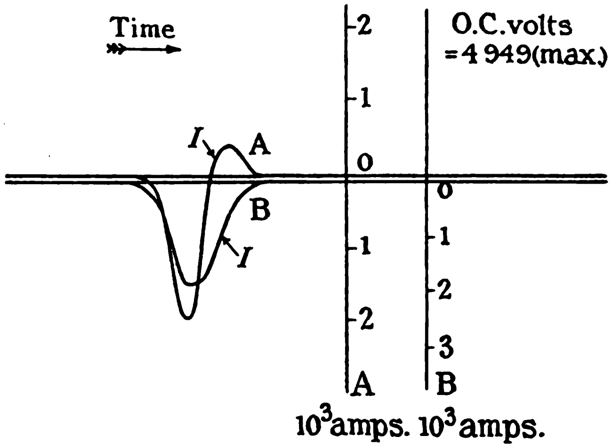

FIG. 30.—Preliminary short-circuit tests on 6 600-volt oil-immersed ironclad cut-out.

With these bi-metallic elements the load/fusing-current ratio was reduced to 1 : 3 and could have been still further reduced.

Fig. 29 shows characteristic time/current curves for fusible elements of this character when immersed in oil under these conditions.

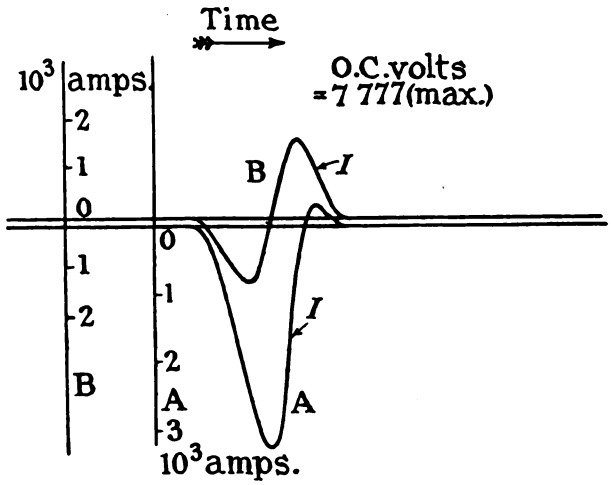

FIG. 31.—Preliminary short-circuit tests on 6 600-volt oil-immersed ironclad cut-out.

Tests on high-pressure oil-immersed cut-out.—Three characteristic oscillograms taken during tests on a 6 600-volt three-phase oil-immersed cut-out are given in Figs. 30, 31 and 32. The first two records were taken on earlier designs operating with a speed of break of about 10 ft. per second, while the third record was taken on the same pattern cut-out after the design had been perfected and the arcing time reduced to the minimum.

Fig. 30.—Three-phase test on dead short-circuit; test volts = 3 500 R.M.S. (line).
Calibration: A = 10·1 mm per 1 000 amps.
B = 7·01 mm per 1 000 amps.
Fig. 31.—Three-phase test on dead short-circuit; test volts = 5 500 R.M.S. (line).
Calibration: A = 9·3 mm per 1 000 amps.
B = 6·5 mm per 1 000 amps.
Fig. 32.—Three-phase test on dead short-circuit; test volts = 6 500 R.M.S. (line).
Calibration: A = 6·05 mm per 1 000 amps.
B = 8·66 mm per 1 000 amps.

The ironclad oil-immersed cut-out is available for higher pressures than 6 600 volts, but no tests have

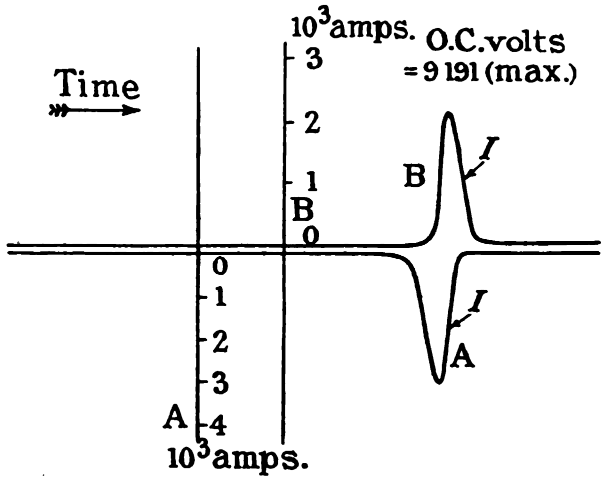

FIG. 32.—Short-circuit test on final design of 6 600-volt oil-immersed cut-out with high-speed break.

been carried out by the author on the higher-pressure cut-outs.

A characteristic time/current curve of a high-pressure oil-immersed cut-out is given in Fig. 33. The feature to be noticed in this curve is the tendency towards flattening of the characteristic from the rather angular form of similar air cut-outs.

Oil and gas pressures in oil tanks.—When an oil cut-out is interrupting any considerable current, pressures are set up which are to some extent a measure of the power being ruptured.

If the power broken is well within the capacity of the cut-out, the effect of the arc is to set up a hot gas bubble in the body of the oil. A steep-front pressure-wave will then be transmitted to the walls of the tank. This wave may or may not be capable of doing material damage. After an interval, the oil will yield to the pressure, which will cause an upward movement of the oil (the only direction possible), but, owing to the power being comparatively small, the air at the top of the tank will be compressed, but only to a small extent. The movement of the oil and air will adjust the pressure sustained after the original explosion.

If a greater power be broken, the high-frequency

pressure-wave will be of greater amplitude. The follow-on effect due to the expansion of the gas bubble will be greater and the oil will be pressed out in all directions against the top, sides and bottom of the tank. The air cushion will be practically obliterated and a pressure will be sustained in all directions. A mental picture of the condition can be obtained by considering the gas bubble to be a core to the oil, the latter being held securely in all directions against further expansion by an iron skin, i.e. the oil tank.

In short-circuit tests at 6 000 volts a number of oil-pressure records were taken. When breaking 10 000 kVA the sustained pressures averaged nearly 20 lb. per square inch. At 20 000 kVA the average

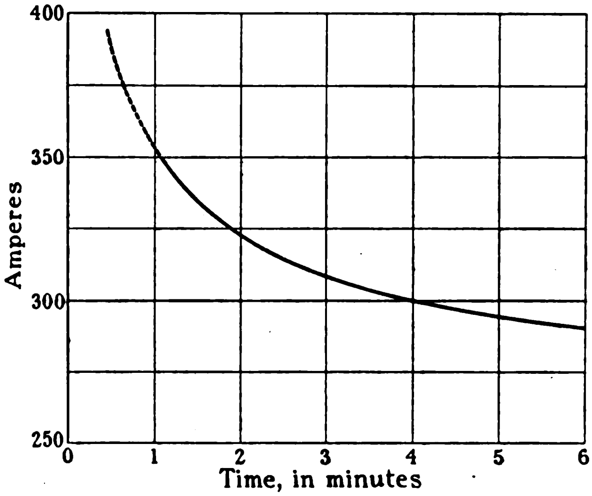

FIG. 33.—Time/current curve of copper fusible element in oil.

of a number of tests gave nearly 30 lb. per square inch, and at 50 000 kVA the pressures reached 150 lb. per square inch several times, but averaged more nearly 80 lb. per square inch. In Fig. 34 are given curves showing comparative results obtained in similar tests. Curve (A) gives the average pressures, whilst curve (B) gives the maximum results recorded. It should be explained that whilst in the majority of instances the pressures recorded are in the neighbourhood of curve (A), yet there is, at present, an ineradicable proportion of pressures recorded of quite a different order. These exceptional pressures are referred to as maximum

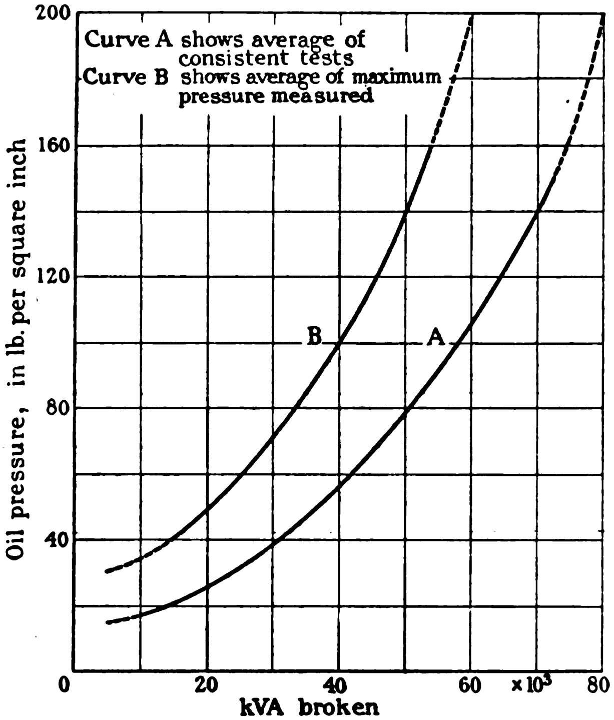

FIG. 34.—Curve showing average and maximum oil pressures set up when rupturing a given power.

pressures and their average values are recorded in curve (B). It is considered that all cut-outs should be designed for at least the average of such maximum pressures. In all tests these pressures were measured at the tank walls or bottom. The curves, it will be seen, do not cut the zero, perhaps because so soon as the gas bubble becomes large enough to press out the

TABLE 2.

Oil-Immersed Fusible Cut-Outs.

Bi-metallic Fusible Elements under Oil but not under Tension.

Horse-power	Standing amperes per phase	Load amperes per phase	Stalling amperes	Fusing current at 2 secs.	Fusible element to be used
Below 10	80	12	48	77	17 S.W.G. tin (not bi-metal)
10	105	15	60	105	(Bi-metal), 0·053 in. outside diam.
20	180	26	104	175	(Bi-metal), 0·067 in. outside diam.
30	280	40	160	320	(Bi-metal), 0·113 in. outside diam.
50	490	70	280	450	(Bi-metal), 0·137 in. outside diam.
75	700	100	370	750	(Bi-metal), 0·177 in. outside diam.
125	1 000*	180	700	1 200	(Bi-metal), 2 × 0·177 in.

* Assumed.

oil in all directions, a pressure of at least 20 lb. per square inch is set up. Several arrangements were devised in attempting to produce a reliable pressure indicator for this work, and it is believed that the results given are to be relied upon.

Ratings of oil-immersed cut-outs.—The low- and medium-pressure type of ironclad oil-immersed cut-out above referred to is rated for pressures up to 660 volts between phases. This type is also modified for high-pressure work for voltages between 2 200 and 3 300. Both types have been tested many times and are capable of breaking 60 000 kVA satisfactorily. The maximum safe rupturing capacity is probably between 80 000 kVA and 100 000 kVA.

The particulars given in Table 2 are an example of a typical rating system for low-pressure and medium-pressure cut-outs, and are applicable to power station auxiliary motors controlled by voltage-reducing starters or their equivalent, but do not apply to direct-started motors. The figures are based on a motor efficiency of 80 per cent and a power factor of 0·80. The cut-outs are required to withstand the full starting current for 2 seconds without blowing, but should clear a sustained stalling current.

Table 3 contains particulars of a simple fuse-rating system for cut-outs of the high-pressure type and gives for the various fuse sizes the load current and load kVA at various voltages, as well as the rated rupturing capacity at those voltages. For load ratings above those given in the table, it is usually more economical to install oil-immersed switchgear.

The various types of ironclad oil-immersed cut-outs have been proved capable of breaking load current and isolating a high-pressure circuit merely by swinging back the lid, without affecting the fusible elements. It is possible to close the lid, thus making the circuit on full load and on moderate short-circuits with safety.

Table 3.

High-Pressure Oil-Immersed Cut-Outs.

Minimum fusing current	Fusible element (bi-metal)		2 750 V		5 500 V		11 000 V		22 000 V		33 000 V	
	External diameter	Diameter of copper core	Maximum load (approx.)		Maximum load (approx.)		Maximum load (approx.)		Maximum load (approx.)		Maximum load (approx.)	
amps.	in.	in.	amps.	kW	amps.	kW	amps.	kW	amps.	kW	amps.	kW
60	0·053	0·011	20	100	20	200	20	400	20	800	20	1 200
90	0·067	0·015	30	150	30	300	30	600	30	1 200	30	1 800
190	0·113	0·021	75	375	75	750	75	1 500	75	3 000	75	4 500
240	0·137	0·025	100	500	100	1 000	100	2 000	—	—	—	—
350	0·177	0·036	150	750	150	1 500	—	—	—	—	—	—
650	—	—	300	1 500	—	—	—	—	—	—	—	—
Rupturing capacity	—	—	80 000 kVA		100 000 kVA		150 000 kVA		200 000 kVA		300 000 kVA	

New Type of Oil-Immersed Fusible Cut-Out.

Fig. 35 is an oscillogram taken during a test on a new form of cut-out. The fusible element is oil-immersed and the arc characteristic can be consistently reproduced. It will be seen that the arc voltage is quite stable, there being none of the vicious harmonics usually found in an arc characteristic. The process of rupture, as shown in the oscillogram, is clean and rapid and the performance quite different from anything previously experienced, the total energy being much less than with cut-outs of the older forms.

In the test illustrated, the cut-out cleared a short-circuit power of 3 673 amperes at 4 666 volts without any visible or audible evidence of its having operated at all. The overall dimensions of the cut-out are comparable with those of many of the old forms of cartridge cut-out in common use, which in the tests described in this paper proved to be inadequate. It is hoped that more information will be available in the near future.

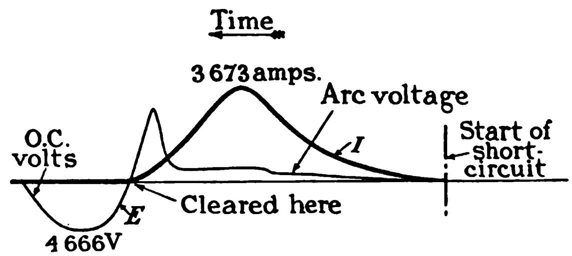

Fig. 35.—Short-circuit test at 5 000 volts on stabilized arc cut-out.

Comparison of Various Types of Cut-Outs.

As the result of the investigations above described, a chart has been prepared with the object of showing a comparison between the rupturing capacities of the

various types of cut-outs tested. This chart is shown in Fig. 36, the ordinates (indicating rupturing capacity) being given on a square-root scale in order to save space. The ninth column (high-pressure oil-immersed cut-outs) has been extended to 300 000 kVA on the evidence of the performance of oil-immersed circuit breakers of similar dimensions. It will be noticed that rupturing capacities above about 5 000 kVA are obtainable only with the modern types of cartridge cut-out with special fillings and with the ironclad oil-immersed cut-outs. One term used in the chart may not be quite clear. In column 4, by "assisted air cut-outs" is meant those cut-outs which consist substantially of a simple element in air and in a carrier or container, this rupturing process being assisted by embodying in the design a pressure chamber or a gas jet as, for instance, in the "expulsion" cut-out.

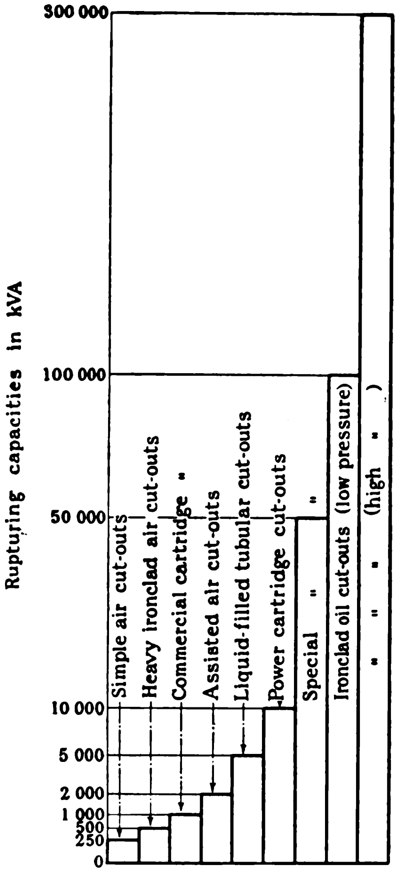

FIG. 36.—Rupturing-capacity chart.

CUT-OUTS FOR SMALL-CURRENT HIGH-PRESSURE WORK.

General remarks.—Experiments were made with a view to finding a fusible cut-out suitable for small-current high-pressure work—for example, for the control of small equipments, the protection of potential transformers and for more unusual services such as the power-line control of "wired wireless" equipment. For this purpose, tests were carried out on tubular cut-outs, many of them similar in form to those already described but using limiting resistances connected in series. It was found that the majority of the better designs could be made to function quietly with a series resistance which limited the short-circuit power to something under 1 000 kVA. These were power cut-outs and relatively expensive. If the value of the resistance be increased to allow lighter cut-outs to be used, the accuracy of the instrument transformers is liable to be interfered with.

Upon reducing the value of the limiting resistance, it was found that two things happened: failure of the cut-outs commenced, and it was found difficult to produce a resistance which could safely be put forward for enclosure in switchgear structures. This is only to be expected as the heating is proportional to the square of the current, and the bulk of the resistance increases in proportion if the resistance is to be capable of withstanding the heating, without damage to itself or neighbouring apparatus. A switchgear enclosure is far from an ideal place for a hot body, such as a limiting resistance when carrying short-circuit current, and there is a real danger of the hot vapour causing flash-over, damage to insulation, etc., or of the resistance itself being destroyed.

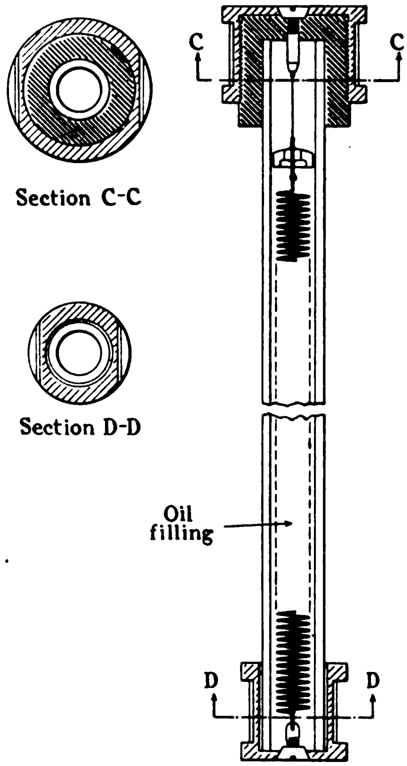

FIG. 37.—Section of resistance cut-out.

Combination resistance-fuse.—As the fusible element would inevitably be destroyed on short-circuit, and as an economical resistance would be in danger of destruction or would rise to a temperature which would be dangerous to other apparatus unless the resistance

were enclosed, it was therefore reasoned that the resistance and fuse could well be enclosed in a single container, thus obtaining a dual advantage. Having a resistance in series, it became possible to design a cut-out of comparatively simple construction which would rupture the maximum short-circuit current and, as the

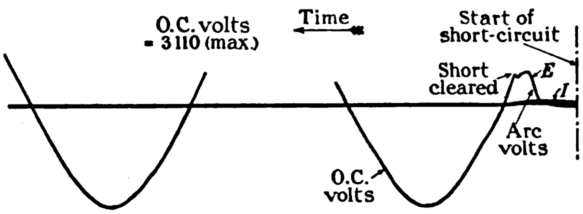

FIG. 38.—Short-circuit test at 2 200 volts on 5 500-volt resistance cut-out.

resistance was enclosed with the cut-out, it was relatively unimportant if this resistance should become overheated.

Following to some extent on the experience obtained on the ironclad cut-out, a short fusible element was used. This was immersed in oil in a tubular

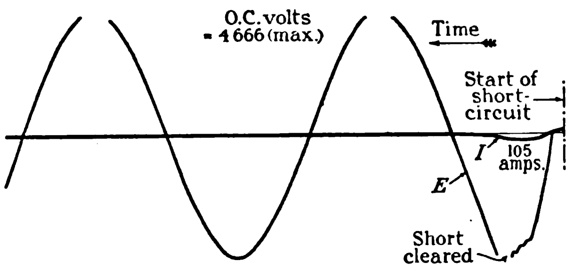

FIG. 39.—Short-circuit test at 3 300 volts on 5 500-volt resistance cut-out.

container as shown in Fig. 37. The resistance wire was made in the form of a spiral to obtain the requisite resistance and to take advantage of the magnetic effect of the turns of the spiral in obtaining a rapid break. A short element was used giving the desirable

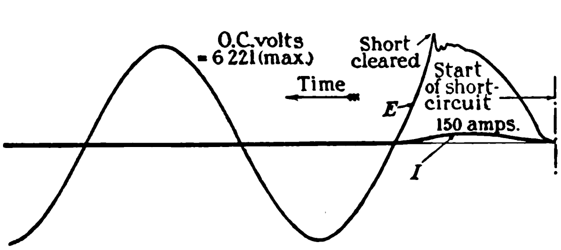

FIG. 40—S.hort-circuit test at 440 volts on 5 500-volt resistance cut-out.

feature of having only a small mass of metal to be melted. Tests were carried out on this cut-out and finally resulted in the production of a workable arrangement which could be connected directly across a high-pressure circuit and which interrupted the resultant power without noise, flash, or other unwanted phenomena. Figs. 38, 39, 40, 41 and 42 are oscillograms showing the performance of this arrangement better perhaps than any other description. These tests were carried out at a frequency of 40 cycles per second.

Tests on small-power high-pressure cut-outs.—Particulars of a series of tests carried out on ordinary cut-outs suitable for potential transformers and small-power supplies at high pressures are given below. The cut-outs were rated for 3 000 to 11 000 volts and were of various forms. Some were small and light, whilst others were quite heavy in construction. Containers were variously of glass (which, in spite of its disadvan-

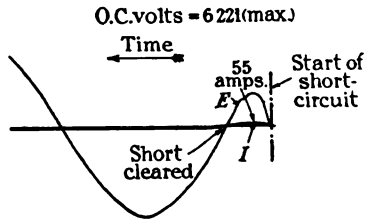

FIG. 41.—Short-circuit test at 5 000 volts on 5 500-volt resistance cut-out.

tages, seems to be a great favourite), bakelite, fibre, etc. Fillings were employed in a great many of the fuses, chalk and marble dust being the most common. The tests are illustrated by means of a representative set of oscillograms.

A feature found to be common to small cut-outs is shown perfectly by these tests, i.e. either the circuit is interrupted in the first half-cycle with extremely low arc energy, indicating good operation, or, in the event of failure of this rapid-extinction process, the arc persists or tends to grow, resulting very quickly in the destruction of the cut-out by the bursting and burning

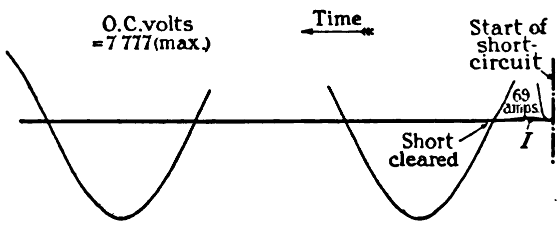

FIG. 42.—Short-circuit test at 5 500 volts on 5 500-volt resistance cut-out.

of container and contact arrangement. It appears to be the rule—and it seems a logical one—that unless such light cut-outs can be designed to clear early in the first half-cycle, they will immediately be destroyed and a dangerous arc across the main contacts will be set up.

Such an arc in the open air persisting for a fraction of a second would result in the destruction of surrounding apparatus and would probably cause a lengthy shut-down. Should the cut-out break up, something is radically wrong with the design—usually the construction is too light.

Tests on Small-Power High-Pressure Cut-Outs With and Without Limiting Resistance.

Small glass-tube cut-out (about 12 in. long and 1 in. in diameter) in air with 380 ohms in series, test voltage = 5 500, frequency = 40: cleared satisfactorily (Fig. 43).

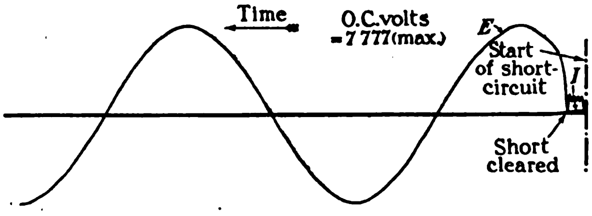

Fig. 43.—Test at 5 500 volts on 5 500-volt glass-tube cut-out with external resistance of 380 ohms.

Element in small-diameter glass tube of switch oil, diameter of tube ½ in., length 14 in., with 20 ohms in series, test voltage = 5 500, frequency = 40: glass burst but cut-out cleared (Fig. 44).

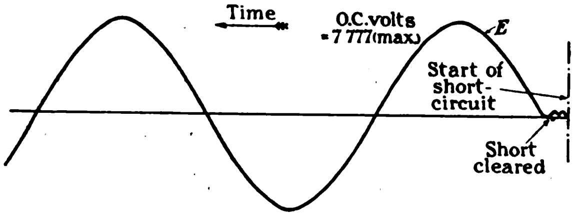

Fig. 44.—Test at 5 500 volts on 5 500-volt glass-tube cut-out with external resistance of 20 ohms.

Element in glass tube filled with marble dust, sealed and immersed in oil tank, no series resistance, test voltage = 5 500, frequency = 40: loud report, tube shattered to fragments, not much gas (Fig. 45).

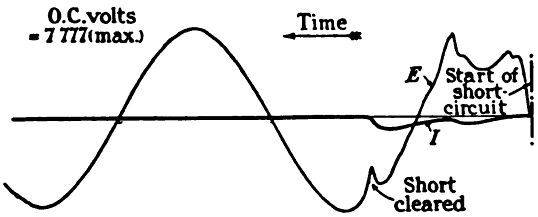

Fig. 45.—Test at 5 500 volts on tubular, marble dust and oil 5 500-volt cut-out without external resistance.

Glass-tube cut-out in mica dust, in air, test voltage = 5 500, frequency = 40: top of tubular container blown through wall, flash and loud report, cleared (Fig. 46).

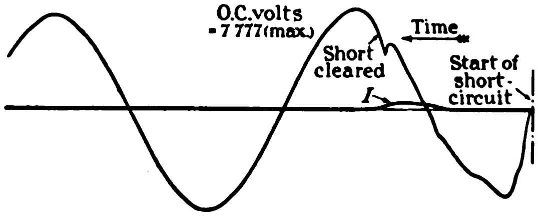

Fig. 46.—Test at 5 500 volts on 5 500-volt mica-filled tubular cut-out without external resistance.

Glass-tube cut-out (small-diameter resistance-wire element) containing marble dust, test voltage = 5 500, frequency = 40: short-circuit cleared (Fig. 47).

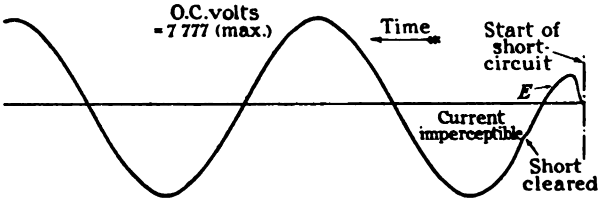

Fig. 47.—Test at 5 500 volts on 5 500-volt resistance-wire marble-dust-filled cut-out.

Small-diameter spring-loaded glass-tube cut-out filled with resin containing element with series resistance of 20 ohms, test voltage = 5 500, frequency = 50: short-circuit cleared, slight noise.

Spring-loaded element in glass tube of small diameter and filled with oil with series resistance of 50 ohms, test voltage = 5 500, frequency = 40: short-circuit cleared.

Glass-tube cut-out in marble dust and sealed and immersed in oil, series resistance of 50 ohms, test voltage = 5 500, frequency = 50: short-circuit cleared.

In the tests with series resistances, the current was so small—probably reaching at the most 100 amperes—that accurate measurements were not possible by oscillograph. Rapid melting of the fusible element is essential if good operation is to be secured. It is not sufficient to ensure that the circuit is cleared in half a cycle, as the current may rise to a maximum in such circumstances. The limiting effect which is so essential is secured only if the fuse is melted on the initial rising-current curve.

Conclusions.

The investigations were commenced because of the confusion of ideas which apparently prevailed as to what was required of a high-power fusible cut-out, and also because of the difficulty of obtaining cut-outs capable of fulfilling all the requirements of the service for which they are intended. It is considered that all cut-outs should be capable of clearing without any explosive effect the maximum short-circuit power of the system or apparatus controlled.

The paper contains an analysis of the factors influencing the rupturing capacity of cut-outs. The load/fusing-current ratio (i.e. the ratio of the full-load current to the minimum fusing current), which depends to a large extent on the cross-section of the fusible element, is found to have an important bearing on rupturing capacity, and great advantage results from keeping it at a low value.

The application of magnetic blow-out appears at present to be of doubtful value, but further tests are perhaps required to settle this matter. The simpler

forms of magnetic blow-out have been found to be the more satisfactory.

The form and strength of the enclosure of a cut-out are of vital importance, and the tests have shown that many existing types of container are not good enough. Fillings for cartridge cut-outs also require close attention in order to be consistently effective. Reliable forms of enclosure and fillings have been tested and are described in the paper.

An elaborate series of tests was carried out, mainly with the object of finding fusible cut-outs suitable for heavy-current work at pressures up to 600 volts, at pressures between 600 volts and 3 000 volts, and also for medium-current and comparatively heavy-current high-pressure work involving the rupturing of powers up to 300 000 kVA. The tests cover up to 70 000 kVA only and were carried out on many different types of cut-out.

Plain fusible cut-outs in air were found to be extremely dangerous for high-power work.

A large number of commercial forms of cartridge cut-out failed to satisfy requirements, but one or two modern forms with carefully designed containers and special fillings were found to be reliable.

Ironclad oil-immersed cut-outs have been developed and are found to be satisfactory within wide limits. Designs have been produced for voltages up to 33 000, and have rupturing capacities beyond the powers available in the tests.

Tests were also carried out on cut-outs intended for small-current high-pressure work, for example for the control of potential transformers and for rural and other small services. The tests showed that the light high-pressure cut-outs available were incapable alone of fulfilling the requirements, but that the majority of them could be made to function satisfactorily if provided with a limiting resistance in series. It is, however, very difficult to arrange a separate limiting resistance in such a manner as to be wholly satisfactory, and a combined resistance cut-out has consequently been developed. This resistance cut-out is described in the paper and has been fully tested with satisfactory results. It is available for all voltages up to 132 000.

As the result of the investigations it has been proved that satisfactory fusible cut-outs are now available for the following requirements (the type of cut-out being indicated in brackets) :—

(*a*) For interrupting powers up to 70 000–100 000 kVA at pressures up to 600 volts (the ironclad oil-immersed cut-out, low-pressure type and the double-tube cartridge cut-out).

(*b*) For interrupting powers up to 60 000 kVA at high, medium and low pressures (single- and double-tube modern cartridge cut-out).

(*c*) For interrupting several hundred thousand kVA at high pressures (the ironclad oil-immersed cut-out, high-pressure type).

(*d*) For small-current high-pressure work (the combined resistance cut-out).

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DISCUSSION BEFORE THE INSTITUTION, 18 MARCH, 1926.

Mr. R. W. Gregory: The primary duty of all interrupters, whether fuses or switches, is to protect the system. It is only a secondary duty to prevent damage to the apparatus which has failed. If the interrupters provided perform both duties satisfactorily, so much the better; but the first duty is the more essential. It appears from the author's tests that a properly designed fuse, rated for its job, clears a fault in half a cycle. It therefore produces the least effect on the system and at the same time protects the faulty apparatus to the greatest extent. The author has shown that there is no inertia in a fuse, whereas any automatic switch takes somewhere about 0·2 sec. to operate. Fuses are very similar in behaviour to the high-speed breakers which have become the fashion on traction work. It is found in practice that these high-speed breakers, which break the fault current in a few thousandths of a second after the incidence of the fault, are so useful in preventing flash-overs on machines that the designers of rotary converters for heavy traction work rely on the installation of these breakers to save their machinery. At the same time the use of these high-speed breakers reduces to a minimum the damage to the faulty equipment. The fuse is a high-speed breaker which is applicable to a.c. work at all distribution pressures. The author's work of sorting out and rating the various types of fuses available for industrial purposes is extremely valuable. Every now and again a minor disaster occurs on growing systems which shows that the fuses installed are not suitable for the increased duty put on them by the growth in generating plant. The author's tests and tables help us in the choice of fuses suitable for modern requirements. The author shows that "open type" fuses are very limited in their rupturing capacity. I know they are very dangerous. A recent failure of a porcelain-handled fuse that I know of might easily have killed any person then in the switch room. It is very satisfactory to know that there are now obtainable reliable powder-filled fuses and oil-immersed fuses to meet present-day requirements. It is perhaps fair commercial engineering to take advantage of the infrequency of the worst possible fault. I should say that for rural supplies on second-class high-pressure overhead lines, which are protected by proper interrupters where they are connected to the main system, it is sometimes quite sound engineering to use some of the low-breaking-capacity fuses tested by the author, even though these fuses will blow to pieces when attempting to clear a fault between phases on the transformer terminals. On the other hand, if a small transformer is connected to an important trunk feeder on the main system, I do not think, from the point of view of the system, that it is justifiable to take such chances; either a first-class breaker, or, what may be cheaper, an oil-immersed switch-fuse should be used. The paper records a very great advance in the art of simple overload protection. I think that the development of the use of fuses will be hindered not by the fact that they are unable to deal with short-circuits (I believe that there is no doubt that they can be made able to deal with any short-circuits with which it is practicable to deal by a circuit breaker) but by the lack of knowledge of what can be done in the way of discrimination. If two or three fuses are in series, it is very undesirable for No. 1 to blow when only No. 3 should blow. I think that this side of the subject of fuse design is worthy of continued research, and I suggest that the author should undertake it. The characteristics of the oil-immersed switch-fuse are worthy of note. I feel that this piece of apparatus is a decided help in the problem of dealing with small powers on important high-pressure systems, a problem which has to be faced by many of us in the power-supply industry at the present time.

Mr. P. D. Morgan: In the past the scientific study of

fusible cut-outs has been very much neglected, and, as a result, engineers in general have been led to assume that such apparatus could not be relied on as a safeguard where large amounts of power were to be controlled. The test-results given in the paper show clearly that the foregoing is an erroneous conclusion, and demonstrate that fusible cut-outs, when designed from data obtained as a result of careful research, can be made to operate in a safe and reliable way under heavy short-circuit conditions. The first point I should like to raise is that of nomenclature. Before any considerable advance can be made in the study of any scientific subject it is well recognized that all the terms used to denote the various quantities to be dealt with must be clearly defined. I noticed in this connection that some of the terms used by the author differ, somewhat from those used by other investigators. For example, his term "minimum fusing current" corresponds to the term "normal fusing current" as used in B.S.S. No. 88 of 1919, and to the term "minimum blowing current" as used by the Electrical Research Association. Similarly, the author's term "load current" corresponds to the B.E.S.A. term "working current," and to the Electrical Research Association's term "rated carrying current." Although those differences may seem relatively unimportant, they have been found to create a great deal of misunderstanding. This point was very clearly demonstrated some three years ago, when the E.R.A. prepared and issued to its members a critical résumé of published information on fusible cut-outs from British, Continental and American sources. As a result of the study of this information, it was found necessary to revise completely the nomenclature on this subject; and, consequently, the E.R.A. report contains a list of most of the quantities and their definitions likely to be met with in a study of this subject. Those definitions are now under consideration by the Editing Committee of the B.E.S.A. and it is hoped that they will be adopted as standards in the near future. The second important point raised by the author is the question of the deterioration of the fuse links of cut-outs under working conditions, and its influence on the subject of rating. He states that the influence of factors such as mechanical vibration, changes in temperature due to load variation, air draughts, etc., are fairly well understood and have been dealt with by other investigators. I think that this statement is only true to a limited extent. It is common knowledge that these factors do influence deterioration; but, despite careful study, the E.R.A. was not able to find any really reliable test-results which showed the exact percentage for which each factor is responsible in a given case. The study of the rating of fuse links from the standpoint of deterioration under working conditions is one in which the E.R.A. is highly interested. In the past few months a great number of tests have been made on this subject; and the results are now being embodied in a report. Much interesting and useful information has been obtained; and further tests will be put in hand shortly. Considering now the question of rupturing capacity of fusible cut-outs, the limit of rupturing capacity of a cut-out is reached when it fails to open a circuit in an "efficient" manner, that is to say, without causing damage by arcing, explosion or otherwise. In dealing, therefore, with rupturing capacity, it appears necessary to define what exactly is meant by "failure." For example, the Bureau of Standards in 1916,* when carrying out extensive short-circuit tests on cartridge fuses, recognized six types of failure, namely: (*a*) Rupturing of the fuse cartridge, (*b*) Blowing off of the cap, or blowing out of the ends; (*c*) Mechanical injury to the cut-out; (*d*) Ignition of cotton placed around the cartridge fuse; (*e*) Holding of the arc for an appreciable length of time; and (*f*) Remaking of the circuit after it had once been opened by the cartridge fuse. It seems, therefore, that the results of the author's tests on cartridge fuses would have been much enhanced if some such criteria had been adopted. In judging the behaviour of the oil-immersed ironclad cut-outs developed by the author, it is to be remembered that the tests were made on alternating current only; whether, in the case of low-voltage tests, similar results would have been obtained in a direct-current circuit under otherwise similar conditions, is open to question. Under existing regulations in Germany, America, Switzerland, France and England, the rupturing capacity of a fusible cut-out for operation at pressures up to 750 volts is based on its behaviour under short-circuit test in a direct-current non-inductive circuit, the current being supplied by a battery of stated capacity. The generally accepted view, therefore, is that these are the most severe conditions for test. As an example of the behaviour of similar cut-outs on a.c. and d.c. circuits, Dr. E. B. Rosen, in the Bureau of Standards tests to which I have already referred, states, as a result of oscillograph tests, that cartridge fuses which are uniform in behaviour on a d.c. circuit vary widely in their behaviour on alternating current. This violence depends on whether the current is broken when there is a large or small amount of energy in the a.c. circuit, that is to say, "it is a matter of chance as to whether the current or voltage is large at the moment that the fuse melts and is interrupted; or whether it has an intermediate value or a zero value." For this reason I think it would be interesting if the behaviour of the cut-outs could have been compared on both alternating and direct current. The E.R.A. is fully awake to the possibilities of the development of fusible cut-outs. By the courtesy of the London, Midland and Scottish Railway the Association has obtained the loan of a large battery at Stonebridge Park power station, capable of giving about 10 000 amperes at 600 volts. A suitable building has been erected, and the work of equipping it with what is undoubtedly the latest design in this country of oscillographs and other apparatus is now proceeding. Starting with tests on existing designs, it is hoped to make an exhaustive study of the various factors underlying the successful design of fusible cut-outs, and to develop a new and improved product.

Mr. H. W. Clothier: The author has been fortunate in having at his disposal a large plant for short-circuit tests. The absence of this in the past has been a great obstacle to the full study of breaking capacities of large fuses, and optimistic ratings have therefore often gone

* "Investigation of Cartridge Enclosed Fuses," *Bureau of Standards Bulletin* No. 74, 1916.

by unchallenged and unchecked. Another obstacle has been the lack of uniformity in demand. The user has failed to state concisely his requirements in respect to breaking capacity. He has been in the habit of merely stating the normal current-carrying capacity without specifying the work to be done or the amount of power behind a short-circuit which is to be cleared. I agree that a cut-out fuse is not satisfactory if in clearing a short-circuit it is shattered or damaged beyond repair for further use, but after all it is a renewable part and not very expensive and so if it does its primary function of isolating the fault it should be pardoned if in the process its condition befits it only for the scrap heap. It is another matter, however, when, as so frequently happens, the original disturbance is spread in an attempt to clear the fault to another more serious fault such as arcing at the terminals or to framework or between busbars. This disability of the ordinary commercial fuse when used on heavy power circuits for which, if the designer only had particulars of testing, he would have known it to be unsuitable, has aroused the author to action. As a result, improvements have been made and a greater expenditure of care and material on the fuse as a protective device is now justifiable. In future I believe we shall endeavour to obtain the isolation of a fault without pyrotechnical displays or secondary damage to neighbouring parts. It will probably become more usual to inquire about the required circuit-breaking capacity before installing a fuse. The author's tests have brought about the necessity for greater care in the smaller power fuses, and he has found that the fuses may enter into the realms of the larger oil circuit breaker, thus providing a more economical form of protection capable of dealing with short-circuits in important locations on large power supply systems. Economies thus effected should more than compensate for the increase in initial expenditure which will probably be caused by bringing to light the defects of the other devices. The meaning of the breaking capacity of a fuse must be properly defined. A general understanding of it is as important as in the case of the ordinary circuit breaker. It introduces a new kind of rating—the author calls it a "potential" power. For example, he refers to a fuse being perfectly safe when opening a "potential short-circuit" of the order of 100 000 amperes. On examining the curve of the performance of this fuse the maximum short-circuit current is shown to be only 25 500 amperes. This is also implied in Table 3, where rupturing capacities are given which are apparently based not on the actual current at which the several sizes would break, but on the amount of potential short-circuit occasioned by a fault in the vicinity of the fuse. In other words, the fuse has a fault-current limiting effect which is not possessed by the ordinary circuit breaker. Advantage may in a measure be taken of this effect by using a smaller form of enclosure for an oil fuse than would be necessary for the ordinary circuit breaker in a similar position on large power-supply systems. A fuse, therefore, requires three power ratings, (1) its normal load, (2) the actual power it breaks, and (3) the potential power that would be available were it not for the restricted effect of the fuse. Bearing on this, the author in Fig. 3 draws attention to the value of a low ratio between the fusing current and the load current. This is all to the good in widening the margin between the actual breaking capacity and the potential breaking capacity, but I am not convinced of the practical value of a ratio so close as 1·2 to 1. I understand that this is obtained by the construction shown in Fig. 4. A fuse may be looked upon to give protection in two ways, (1) as an overload device to protect the plant from excess current, and (2) as a protection for the system by isolating a faulty plant. A low fusing-current/load-current ratio may be useful in the former case, but I am suspicious about so sensitive a margin. It is like using too sensitive a relay on protective gear, as it may tend to cause the plant to be interrupted unnecessarily. If one must have thermal protection to prevent injury to the plant by excessive temperature, then it would seem to be better to provide the plant itself with some simple thermostat device. Moreover, I am not satisfied that in this particular form of fuse there is the advantage which the author claims. As I understand the fuse, it has two main elements, (1) a fusible strip to operate on short-circuit by current, and (2) a fusible bulb of low-melting-point metal to operate on small overload. The device has therefore two time characteristics, but it is on the short-circuit characteristic that its merits as a short-circuit current-limiting device must be gauged. The fusible strip, which is of copper, has, I believe, a fusing-current/load-current ratio of at least 2 : 1, in which case the power ruptured, according to Fig. 3, would be 14 000 kVA and not 6 000 kVA as taken by the author on the overload function of the fuse. As a matter of nomenclature, I doubt whether the author's definition "potential" short-circuit is the best. The word "potential" is apt to be confused with "voltage." The "potential" short-circuit as I understand it is the maximum that would be available in the vicinity of the protective apparatus. A title implying this might be quite as appropriate and less confusing. I suggest "vicinity" short-circuit. I notice that the author uses the word "rupturing capacity," whereas in the British switchgear specifications it is termed the "breaking capacity." The author has in most cases adhered to the B.E.S.A. term "fusible cut-out," but I think it must be admitted that it is a clumsy title and that the word "fuse" comes more naturally to us. It would be interesting to have particulars of the pressure indicators used to record the impulse pressures on the walls of the switch fuse tanks. The most convenient commercial means of testing the strength of tanks is by using an ordinary hydraulic pressure test. Some comparative basis is required to associate the impulse pressure with the steady hydraulic pressure. It is probable that a tank which would withstand the ordinary hydraulic pressure test of 15 lb./sq. in. would be competent to withstand the impulse pressure of 150 lb./sq. in. The author mentions that the oil switch-fuse can be used as a switch to open and close while carrying full load, and can also be switched in on *moderate* short-circuits. As a safeguard against the possibility of closing this isolating device on a heavy short-circuit I prefer to equip the lid with a separate isolating switch

in those cases where there is no other isolating switch in the circuit. This improved type is provided with an interlock which prevents the isolating device from being in a closed position when the operation of closing the lid is in process, and guards against the possibility of contact being made on a short-circuit before the lid is completely closed. It must be observed that it would be risky to an operator who happened to close the lid on a heavy short-circuit in the arrangement shown in section in Fig. 27 and in the elevation in Fig. 28. It is noteworthy that over 30 years ago the oil-break fuse was made by Dr. Ferranti. Comparing the features then and now, the old oil fuse obtained isolation by withdrawal of the fuse from fixed contacts (but not on load), it had the spring break, and the moderate blow-out now recommended by the author was obtained by taking the fuse at right angles to the two parallel conductors which lead to it. It had the advantage of having the actual fuse wire normally in air, the contacts being drawn down into the oil. What it lacked as compared with the present-day device was the strong metal-clad enclosure, oil-tight joints and sufficient clearances between terminals to avoid arcing over terminals after the fuse had blown. I think that the author's work will in the future be of great service to electric supply distribution, particularly in the control of small supplies to rural districts and to outlying consumers where the cost of the more expensive forms of switchgear with circuit breakers would be a handicap to extensive developments on supply undertakings.

Mr. A. Hooker: There would appear to be a considerable field for fusible cut-outs in connection with rural supplies from high-tension systems which are, very probably, often inadequately provided for with respect to short-circuits. I recently examined some of the high-power cut-outs on the market, and was impressed with their design and structure. The container is made of glass filled with CCl_4, and there is a separate fuse chamber. The fusible element is connected by a wire which passes through a nozzle-shaped piece of wood, and is attached to a spring, the latter being held in tension. The fuse chamber has a lid-like cover, sealed with a soft composition. When the fuse blows, the cover is blown off, thus avoiding explosion, and a spring is released, speedily opening the gap. Damping fluid is forced through the vents into the fuse chamber and any arc is extinguished. The makers claim that their fuse is capable of rupturing over 25 000 kVA on the first half cycle with absolute safety. It seems to me to be desirable to have a transparent container wherever possible, if only for inspection purposes. I should like to ask the author whether containers composed of silica containing Cl_4 or tri-chlor-ethylene have been tried? Silica is transparent and is capable of withstanding higher pressures and temperatures than is glass.

Mr. P. Dunsheath: The paper leaves one with the impression that the author, in his enthusiasm for his subject, has rather overlooked the necessity for logical treatment, and in my opinion it would have been of advantage if he had added definite conclusions to be derived from some of the tests. Several speakers have already referred to the questions of nomenclature and fundamentals, and I think that the value of the paper would be considerably enhanced if the author could deal with that point a little more fully in his reply. For instance, if he had properly defined the ratio of the fusing current to the working current the subject would have been more easily understood. Again he speaks first of all of the necessity for reducing a load-current fusing ratio, and a few lines later he talks of reducing the fusing-current/load-current ratio. Both cannot be right. I suggest that the name of "ultimate current ratio" should be given to this quantity. The author does not appear to deal with the 1-minute fusing current in the paper. I think that is rather a serious omission in view of the fact that many people are working on it to-day, and the "1-minute current ratio" is another important quantity. Fig. A demonstrates these two current ratios and illustrates two points that the author, if I may be allowed to say so, makes rather laboriously, namely, the effect of altering the ratio. He says that if the ratio of minimum fusing current to working current is increased for a given working current, the load to be broken on the fuse is increased. It is quite clear from Fig. A that when the ratios are increased the fusing current curve is raised and this increase naturally increases the current at any particular time. In the same way, the author says that if the same ratio is decreased, the fusing current being kept constant, the working temperature is raised. The diagram again shows in a very simple way that to reduce the ratio with a constant fusing current simply raises the working current load, and so increases the temperature of the fuse under working conditions. In the same connection Fig. B shows some other results which have

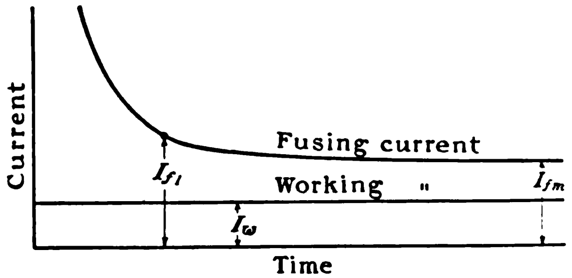

FIG. A.—Current ratios.

$$\alpha = \text{1-minute ratio} = \frac{\text{1-minute fusing current}}{\text{working current}} = \frac{I_{f1}}{I_{\omega}}$$

$$\beta = \text{ultimate ratio} = \frac{\text{minimum fusing current}}{\text{working current}} = \frac{I_{fm}}{I_{\omega}}$$

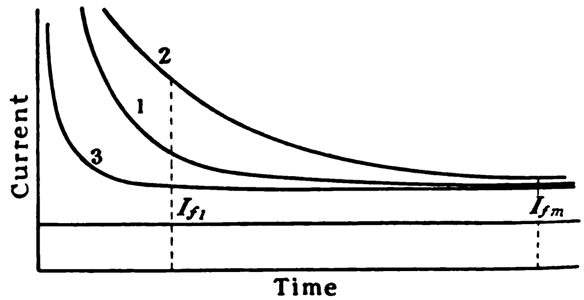

FIG. B.—Effect of material and conditions on shape of fusing-current curve.

been obtained from experimental work and brings out the effect of different materials and different conditions on the shape of the fusing-current curve. The inner curve is of a copper wire in air. It will be seen that the 1-minute current ratio and the ultimate current ratio are practically the same. If the wire is replaced by a low-melting-point metal, we get curve 2. If the ratio in the first place is something of the order of 2, the supposition made in the Institution Wiring Rules, the substitution of tin for copper brings up the ratio to 4 under certain conditions. At the same time the ultimate ratio is not affected. Curve 3 shows the effect of lagging the wire in any way. If, for instance, wire is put in an asbestos tube or a holder of any kind which will retain the heat, then this neck appears in the curve and the 1-minute current ratio is equal to the ultimate ratio. The second main point which I should like to raise goes right to the root of fuse design. I suggest that the author, in common with all previous investigators, has overlooked a vital principal affecting the rupturing capacity. By the application of a very simple physical principle, the rupturing capacity of a cut-out can be enormously increased. An arc is, after all, simply a space which is rendered conductive by ionization. We know that the potential required to ionize is closely connected with the actual mechanical pressure of gas. If the pressure of gas is increased, the requisite voltage is increased at the same time. The rupturing capacity of the fuse is closely connected with the quenching of the arc. From those considerations it follows at once that in order to increase the rupturing capacity, all that we have to do is to increase the pressure of the gas formed when the wire is vaporized. As it happens, air pressure or pressure on the gas is very easy to produce; all that is necessary is to restrict the expansion of the volatilized metal. Many designers have appreciated this factor of pressure due to the restriction of the expansion of the gas, but, so far as I can see, in every case where the characteristic has been made use of it has been accidental. Some designers have introduced vents to enable the gas to be dissipated; others have produced cartridge fuses with fillers for cooling the gases; but, generally speaking, the pressure generated has been deplored rather than made use of by the author and by all previous investigators. Nobody so far has done the obvious thing, i.e. to produce a tubular container for the wire of internal dimensions very little greater than the wire and mechanically designed to withstand the pressure generated. I have not been able to carry this idea beyond the very elementary stage; but, so far as I have gone, this principle has proved to give a better rupturing capacity than has any other principle adopted to-day. I have here a small fuse which consists of a fibre rod or tube with a hole down the centre. It is about $\frac{5}{8}$ in. in diameter and $1\frac{1}{2}$ in. in length, and the hole down the centre is about $\frac{1}{8}$ in. in diameter. On each end is screwed a strong brass cap and between the caps there is a piece of copper wire. That fuse will break consistently every time without failure on 250 volts a current of more than 6 000 amperes, which is the maximum battery current available. It will rupture about 1 500 to 2 000 kW with ease and those who have experimented with fuses will be aware that the results obtained with this small fuse are about four times better than can be obtained, using the same dimensions, with any other types. All that is required, then, is a mechanical design to withstand the high pressure generated. In this particular fuse the pressure generated is of the order of 1 ton per sq. in. The author mentions the importance of quick rupture. This little fuse, when breaking a load of 1 500 to 2 000 kW, only burns away $\frac{1}{2}$ in. to $\frac{3}{8}$ in. of the copper wire. By the time this amount of copper has disappeared the pressure generated is sufficiently great to break the arc, so producing what must be a very rapid rupture.

Mr. Vernon Hope: I should like to refer to Mr. Clothier's point with regard to the fuse element in the Aeroflex fuse. The tin pocket in the Aeroflex fuse is not correctly considered as a second fuse in parallel with the copper main fuse. This tin pocket has a carrying capacity very much greater than the carrying capacity of the copper fuse, and it may be best considered as fulfilling to some extent the function of the lead seal in the Grinnell sprinkler used for the fire protection of buildings. When the temperature of the copper rises above the melting point of the tin, the tin pocket is melted out. The advantage of this arrangement is that the copper portion of the element is run at a low temperature; consequently there is no oxidation of the element, and it is for this reason that the time/current curves take the form they do. With this type of element the fuse can be run at 1 500 amperes for 8 hours, and with an increase of load of 25 per cent the same fuse will blow in less than 5 minutes. With regard to potential-transformer fuses, the general practice of using large limiting resistances seems to be carried to excess and little attempt is made to use a fuse with a high rupturing capacity. Where these limiting resistances are used they occupy a very great deal of space which can be avoided if attention is turned to getting a high rupturing capacity in the fuse itself. We have obtained on test a very high rupturing capacity indeed without any limiting resistance, by the simple expedient of using a silk ribbon in the warp of which is put one strand of very high-resistance wire, obtaining in this way 200 ohms resistance in the fuse itself. In obtaining a high rupturing capacity in a fuse, it is not generally appreciated that there are what one might term two sources of energy. There is the thermal energy due to the melting of the element, and there is what might be called the secondary pressure due to oxidation of the vaporized metal. Uncertain results in fuses are largely due to a want of appreciation of the pressures set up due to this secondary explosion. The primary energy is probably definitely proportional to the rupturing capacity, and the secondary energy is controllable. The secondary energy in the case of oil fuses is a chemical action due to the breaking up of the oil and has given rise to great pressure. The difficulties of isolating and analysing the gases formed are very great, and therefore this rather points to the fact that oil is not really an ideal liquid to use. Probably the solution will be found in the adoption of some other liquid. With regard to pressure fuses, I have done some experiments on the lines indicated by the last speaker, and have obtained surprisingly good results

with very small fuses, but the difficulty is not in small fuses but in large ones. It is not only a question of rupturing capacity but also one of avoiding oxidation and heating troubles. A fuse on the lines suggested might be workable up to 20 amperes, but would be quite impossible if 1 500 amperes is considered. In connection with oil fuses, the maximum pressure to be obtained due to thermal energy at the arc does not exceed 150 lb./sq. in., but in oil fuses pressures ranging up to 100 tons/sq. in. have been found, due to the chemical action, and this points to the necessity for very massive construction. What is really needed is a liquid that will damp out the explosion without any secondary or chemical pressure being set up.

Mr. H. Brazil: It may be of interest if I make a few remarks in regard to a supply undertaking's experience with fuses. For the past 20 years we have been using oil-filled fuses on our 10 000-volt three-phase circuit, and are still using them in connection with motor-generators. These fuses consist of a silver wire enclosed in a brass case which is lined with insulation and open at the bottom. To the bottom end of the silver wire is attached a spring, and the whole of the apparatus is enclosed in a glass tube about 12 in. long, filled with oil to about half-way up the brass case. When the fuses blow, the silver wire is drawn down, and the arcing therefore takes place under the oil. At first, glass tubes about 1½ in. to 2 in. diam. were used, and we had some trouble owing to these bursting, but when we increased the size to 3 in. diameter and about ⅜ in. thick to enable them to stand the pressure, they behaved very satisfactorily. It seems to me that this fuse is somewhat akin to Mr. Dunsheath's pressure fuse, as a considerable amount of oil has to be moved before the pressure is released. With regard to low-tension cartridge fuses, I have used these for a working current of 2 000 amperes on 200- and 400-volt circuits, and they have broken circuit so successfully that it has not been possible to know they have done so until a test has been made with the detector. In this case quite a number of fuses are in parallel, say 20 in the case of the 2 000-ampere size. These fuses consist of stout copper wires joined together in the centre by a small length of silver wire which is brazed to them, the whole being enclosed in a cartridge filled with marble powder. The length of the fuse is about 6 in. I am inclined to agree with Mr. Hope that, while Mr. Dunsheath's pressure fuse may be quite satisfactory with small currents, he would experience serious difficulties when he tried to use them for larger currents.

Mr. A. W. Isenthal (*communicated*): The author mentions several materials used in the construction of fusible elements, but does not mention silver. As is well known, silver oxidizes very slowly, and my experience has shown that silver wire, used in correctly designed tubular holders, forms a very good high-tension fuse. What is the author's opinion of silver fuse wire ?

Mr. J. M. Scott Maxwell (*communicated*): On page 920 it is stated that "At the time the investigations were commenced, the author could not find any cut-outs capable of rupturing, with reliability, heavy currents at medium or high pressures, or any reliable cut-outs suitable for small-current high-pressure use." The "S. & C." fuse, called by the author a "liquid-filled glass-tube cut-out," was well established in the United States before the war. This fuse was invented by power-station engineers to get over many of the troubles mentioned in the paper. It has been submitted to many tests, both in this country and America, and the test data in my possession indicate much better results than those given in the paper. This fuse was originally designed for the protection of potential transformers, thousands of them being installed all over the world, and to the best of my knowledge there have been no accidents due to their use, such as have happened with simpler forms of fuses. The fuses are used without any external resistance, and as almost all potential transformer breakdowns are due to insulation weakness in the transformer and take some time to develop, the fuse clears the circuit before any damage can be done to the system. The operation of these fuses with potential transformers was so satisfactory up to 132 000 volts that they were also developed for power purposes. It is not intended that the power fuse should be installed in the power station, where there is the minimum of impedance between the fuse and the generator. The fuse is intended to be installed on transmission lines and distribution systems, and the latest design of power fuse will break a greater kVA than is indicated in the paper. The following tests were made by the Duquesne Light Co. at the end of 1923, at their North Substation on the 66 000-volt ring, stepping down to 22 000 volts, the fuses being connected across the 22 000-volt side of the step-down transformers. The figures in Table A are from oscillograms.

It will be noted that only in the last test did the

TABLE A.

Test	Fuse rating	Voltage across fuse	R.M.S. current (initial)	R.M.S. current (broken)	Load (broken)	Cleared in
	amps.	volts	amps.	amps.	kVA	cycles
9	50	13 500	3 060	2 080	28 000	2
10	50	13 600	4 910	3 620	49 000	2
11	50	13 500	5 980	5 380	72 000	2
12	50	13 700	5 395	4 980	68 000	2·5
13	50	13 100	?	5 240	68 000	2·5
14	100	13 100	7 260	6 150	80 000	1·5
15	200	13 200	?	5 880	77 000	2·5
22	50	12 800	7 240	6 430	82 000	failed to clear

fuse fail to clear. The same test was repeated with the 100-ampere and 200-ampere sizes of fuse and these fuses both cleared. The tests show that the rupturing capacity of the 50-ampere size is above 5 000 amperes at 13 000 volts across the fuse, or over 65 000 kVA. The 60- to 200-ampere fuses are of larger diameter and have a rupturing capacity of at least 80 000 kVA. Oscillograms of two of the above tests are given in Figs. C and D. Tests were carried out at Carville Station, Newcastle, during 1922, the fuse in this case being connected across the generator with the minimum of impedance on the line. The figures which I have of these tests are given in Table B.

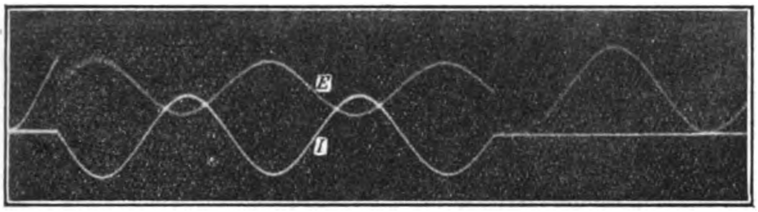

Fig. C.—Test No. 12 (50-ampere fuse).
Voltage across fuse = 13 700.
R.M.S. current { Initial = 5 395 amperes. Interrupted = 4 930 amperes.

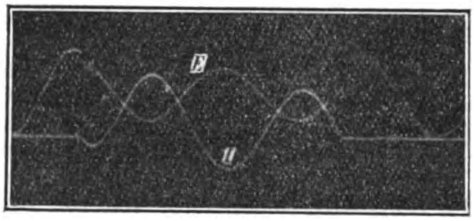

Fig. D.—Test No. 14 (100-ampere fuse).
Voltage across fuse = 13 100.
R.M.S. current { Initial = 7 260 amperes. Interrupted = 6 150 amperes.

Table B.

Fuse rating	Voltage across fuse	R.M.S. current (broken)	Load (broken)	Remarks
amps.	volts	amps.	kVA	
20	6 000	5 300	31 800	failed
20	5 000	4 400	22 000	cleared
20	5 500	4 850	26 600	cleared
20	4 000	3 550	14 200	cleared
20	5 500	4 850	26 600	cleared
20	6 000	5 300	31 800	failed

The fuses which cleared did so in the first half-cycle. They were of the same type and diameter as the 50-ampere size in the American tests, and cleared over 25 000 kVA. The only difference involves a constructional detail, but rather an important one. The top ends of the fuses tested at Carville were sealed with a flat copper disc, soldered at the edge to the brass cap. The pressure required to blow off this disc under a short-circuit, thus relieving the internal pressure, varies according to the soldering. In the latest design which is described below and which was the design used in the American tests, no solder is used. The disc or vent cap is pressed into the brass top, and by using a special paste the joint is made air-tight. This design is more reliable than the older design and requires less pressure to remove the disc, thus raising the effective rupturing capacity of the fuse. The maximum current cleared is approximately the same in both tests, the higher kVA in the American tests being due to the higher voltage. This indicates that with still higher voltages the kVA rupturing capacity will also be higher. In the " S. & C." fuse (see Fig. E) the fusible element is of very small dimensions so that it fuses rapidly and produces the minimum of metallic vapour, and thus the ratio of fusing current to load current is not important in this fuse. As the fuse is hermetically sealed and filled with a liquid and its vapour (CCl_4) in which there is no oxygen, the fuse element is not subjected to oxidation or corrosion. The tension of the strong spring, which is extended twice its length, is taken by a nichrome-steel wire. There is no strain on the fuse element, which in the smaller sizes is of silver wire and in the larger of tin strip. As the steel wire has a high resistance it melts

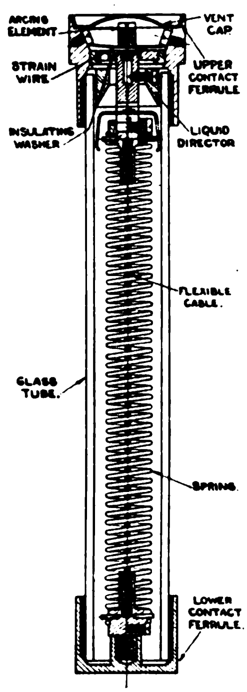

Fig. E.

practically simultaneously with the fuse element and the spring thus draws the live terminal very rapidly into the liquid, the moving parts having very little inertia. The liquid both cools and extinguishes the arc due to its dielectric property, which is over 100 000 volts per inch. The container is a glass tube, as used for

steam gauges, but the pressure does not rise to the high values given by the author. The initial explosion takes place in the brass explosion chamber, the top of which is a saucer-shaped disc, pressed into the end and made airtight by means of a special paste. No solder is used, and the disc is blown off immediately the pressure reaches about 50 lb. per sq. in., whilst the pressure required to break the glass tube of the 50-ampere fuse (1 in. internal diameter) is over 1 100 lb. per sq. in. The amount of liquid in the fuse is small and, as very little is ejected when the fuse blows, no damage is done to other plant nor is there any danger to station attendants. The brass ends are fixed to the glass tube with a special alloy, and the coefficients of expansion of the brass, glass and alloy are such that no leakage can occur at the lowest temperature or in the hottest tropical sun. The fuse requires no protection of any kind, and can withstand every climate. It has been submitted to several competitive tests in America by different official bodies and has given better results than every other make.

Mr. J. B. Rudkin (*communicated*): There can be no doubt that the conclusions drawn by the author are in favour of introducing a new make of oil-immersed fuses. These have, in fact, already been anticipated by similar designs of other makers. Amongst others may be mentioned the Union Switchgear Co. (Voigt & Haeffner), who manufactured a design in 1914 which is practically similar to the one shown in Fig. 26. Many of the introductory criticisms in the paper of existing types of fuses are quite correct, but they are not, however, entirely correct in that certain makers have been able to eliminate many of the weak points referred to. It is claimed that the type of fuses which are now being manufactured in England by the firm with which I am associated, possess very few of the points criticized. There is no question that our low-voltage tubular or switch-handle-pattern fuses are not made for a breaking capacity larger than about 10 or 20 times the rated current. I am of the opinion that in places where the breaking capacity is as high as 50 000 kVA or even above 10 000 kVA, the oil-immersed circuit breaker is the more convenient type of apparatus to use. Regarding potential-transformer fuses, for a number of years we have manufactured these with a series resistance to limit the breaking capacity to values that the fuse can easily deal with. For voltages above 33 000 a weak point, which has not been mentioned by the author, in many existing types of fuses is the deterioration of the fuse wire of very small diameters by radiation. This has been avoided in our designs to such an extent that we can easily guarantee fuse wires to remain intact for voltages as high as 200 kV without any visible sign of deterioration. The use of pure copper has been abandoned on the Continent for high-voltage fuses, on account of instability of section as the result of oxidation. They have been replaced by non-oxidizing metals, silver being mostly used and, in some cases, tungsten. The author strongly criticizes fuse carriers made of porcelain. Up to a certain limit I agree with him, but I must strongly object to his conclusions that no suitable porcelain fuse carrier can be made. My firm has designed and supplied in large numbers a porcelain fuse carrier which will safely break a load of 10 000 kVA under 15 000 volts and even more. We would not hesitate to design air-break fuses of similar characteristics for 2 or 3 times this breaking capacity. On page 925 the author states that an open-type fuse is superior to an arrangement confining the wire in a carrier, but our tests show that this is not generally true. The values given in Fig. 36 do not apply to our types of fuses. Oil fuses have been in practical use in so many different forms that every possible experience has been gained with them, and, as I have already mentioned, the type of fuses shown in Fig. 26 are no exception. The cost of installation and space required for this type of oil-immersed fusible cut-out would be about the same as that in the case of an automatic oil switch; in fact oil switches for 6 600 volts and breaking capacities between 50 000 and 100 000 kVA occupy about the same space and can be bought for the same price. The decision as to which device should be used does not depend entirely on the initial cost. There are many inherent deficiencies in fuses. Of these the continual cost of spare fuse replacement parts, difficult service control by reason of the delay in restoring the service, and electrical shut-down by single-phase interruption producing high-voltage surges, are amongst the most commonly known. The above drawbacks of fuses are mentioned in full appreciation of the many advantages possessed by these devices, but in my opinion the application of fuses in electrical installation must necessarily be limited to cases where continuity of service is not seriously impaired by their action. Even if the fuse, in common with other apparatus, is constantly subjected to improvements in design to enhance its electrical qualities, the service engineer will in every case have to discriminate carefully at which point of the installation fuses may be used, and where circuit breakers are preferable or indispensable. Fuses have up to the present in a general way stood up to their service and given satisfaction, due to the fact that they have been installed in places where the breaking capacity imposed on them is certainly very much below 70 000 kVA for low and medium voltages, and equally below 30 000 kVA for pressures over 3 000 volts. These figures can be easily calculated from the layout and dimensions of the network in any particular case. In installations where breaking capacities of the above magnitude enter into consideration, the question of the resumption of service is of such vital importance—as every engineer who is in touch with relay problems knows—that it is quite impossible to utilize fuses where a scientific system of protection by means of discriminating relays is called for. There is a large demand for high-tension fuses on the score of their low cost for installation and operation. The standard types manufactured by my firm have been fully proved by a large number of engineers both on the Continent and in Great Britain.

[The author's reply to this discussion will be found on page 954.]

North-Western Centre, at Manchester, 16 March, 1926.

Mr. Vernon Hope: There are a few points on which I cannot see eye to eye with the author. In the chart showing the comparative maximum rupturing capacities, he puts the rupturing capacity of the oil fuse at a considerably higher value than the rupturing capacity of what he has called the special cartridge fuse. The rupturing capacity of this special cartridge fuse is arrived at by actual tests which he has carried out himself, but my contention is that the maximum rupturing capacity of the fuse was not reached, and I have a good reason for this contention. We have approximately measured the pressures in these cartridge fuses and the fuses have successfully cleared circuits with a pressure of 10 times the amount that was actually obtained on the particular tests on which the author bases his maximum rupturing capacity, and therefore it is reasonable to contend that there was a very wide margin to spare and that the rupturing capacity of these fuses is very much higher than the figures given in the paper. With regard to the rupturing capacities given for the oil fuses, these are only approximate figures and are based on assumptions founded on results obtained from oil switches, which may not necessarily be correct. In comparing the powder-filled fuse with the oil fuse, it is important to remember that the correctly designed powder-filled fuse has a high rupturing capacity with very little pressure in the fuse case, but the oil fuse has a high rupturing capacity with a very great pressure in the case. The pressure in oil fuses has been found to be thousands of lb. per sq. in., and this pressure is due to the chemical action and not to the thermal energy of the arc. I have therefore still to be convinced that the oil fuse has a higher rupturing capacity than the powder fuse. The oil fuse has many attractive features and in design it is comparatively simple compared with the difficulty in producing a powder-filled fuse with a high rupturing capacity. No doubt some people will disagree with the very low rupturing capacity which the author has placed on the ordinary commercial fuse, but there is not the slightest doubt that in this he is perfectly correct. The ordinary commercial fuse produced to-day is apparently designed without any knowledge of the subject and is a very inadequate means of opening a circuit, but no doubt the time has come when designers will have to pay a great deal more attention to research in the matter if fuses are to be produced with some reasonably high rupturing capacity.

Mr. S. R. Mellonie: The curve shown in Fig. 3 presumably refers to fuses with a ratio of fusing current to load current of 1·2 to 1. If the author has the data available it would be interesting to amplify this by the addition of another curve for fuses wired for a 2 to 1 ratio. The author is to be congratulated upon the development of a satisfactory high-tension oil-immersed fuse of high rupturing capacity, but the pressures shown in Fig. 34 certainly require a design which provides for closing the circuit after the cover is bolted or latched in position. Has the author's fuse any device to give external indication when the circuit is ruptured? Recent tests confirm the author's conclusion (on page 937) that the most economical arrangement for light-power circuits is a simple fuse of cheap construction and a series limiting resistance. The ohmic value required to keep the power within the limit of the fuse is so low that the effect on the accuracy of instrument transformer circuits is negligible. Tests have recently been made on a new design of semi-enclosed wire-wound resistance of robust construction which is quite suitable for use in a high-tension switch cubicle. No danger need be anticipated from the fact that the resistance may, for a fraction of a second, become red-hot, as the heat is quickly liberated. The design shown in Fig. 37 is certainly a neat solution of the resistance cut-out, although the sudden increase of temperature of the mass of the spring in a limited quantity of oil must produce pressures which are absent when the resistance is air-cooled and the fuse a separate piece of apparatus. In view of the author's suggestion that the fuse should break circuit in the first half cycle, the oscillogram shown in Fig. C should be interesting. This may be taken as typical of a number of tests of an expulsion-type fuse

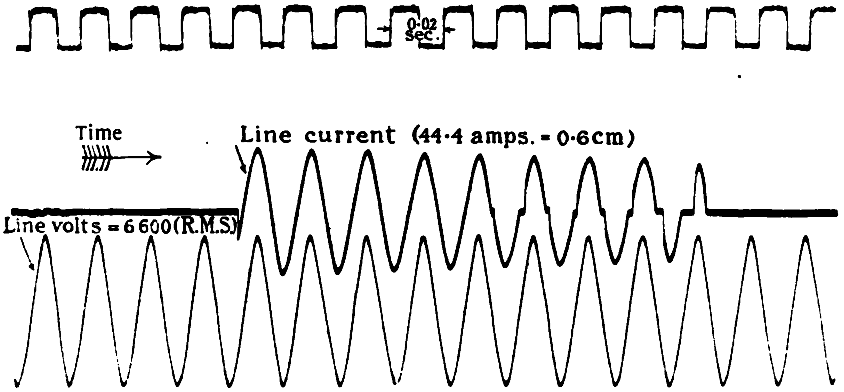

Fig. C.

in series with a limiting resistance; in every case the fuse cleared the circuit quietly and efficiently although the current persisted for several cycles.

Mr. A. B. Mallinson: I have for many years been prejudiced against the fuse, but the development of the cartridge fuse has astounded me. If the author's experiments are carried out on the scale that he has outlined I can understand the need to make tests in the open air. It is only by experiments of that character that we can provide for the practical development of the fuse or any other piece of electrical apparatus. I see one great objection to the fuse and I do not yet see how it will be overcome. The circuit breaker opens and it is re-closed; but what is going to happen to the fuse in industrial areas where the man in charge has not a full knowledge of the subject? I should like to see a fuse so designed that it is not possible to put a metal strip across it. I was very impressed with the way in which the circuit was cleared by the Aeroflex fuses. These blew exactly as the lantern slide showed. I was particularly impressed by the state of the Aeroflex fuses after being short-circuited across a 460-volt 6 000 ampere-hour battery with no resistance in series. I understand the resistance of the circuit was 0·006 ohm and that the fuses, wired for 38 amperes running load, blew at about 1 000 times full load. There was absolutely no sign inside the inner bakelite sleeve, or on the small terminals at the end, of any splashing. That test conclusively shows that a fuse of this character is really a good fuse; it will not be necessary to have a new cartridge complete every time a fuse blows, on a short-circuit. This is an important factor, as the cost of the complete cartridge replacements is high, but the spare fuse element complete with the powder is not a big item. Referring to the oil fuse, how far is it going to be elaborated? Is not the reason for the fuse being developed one mainly of capital cost? If we are going to get massive construction similar to that shown on the lantern slides, I suggest that it will approach the circuit breaker in capital cost, without any step in advance being made.

Mr. B. M. Burt: I think that the most important point in the paper is the claim that a well-designed fuse will clear a short-circuit a considerable time before the current has reached its peak value. In Fig. 3 the author shows that the extent to which this can be done is increased by reducing the ratio of fusing current to load current. It has hitherto been thought that the reduction of this ratio increases the breaking capacity by reducing the amount of metallic vapour; surely the author will still agree that this is a factor and that for this reason alone a copper wire will have a higher breaking capacity than, say, a lead wire having the same minimum fusing current. Whilst agreeing that a wire of very small section can reach its fusing temperature well before the current has attained its maximum value, I do not agree with the author when he states that on a 6 000-volt system having a maximum short-circuit capacity of 70 000 kVA, a 100-ampere fuse with a fusing current of 120 amperes will have to deal with only about 6 000 kVA. No commercial fuse with this blowing current could melt more rapidly than 0·002 sq. in. of copper. For this to deal with only one-tenth of the potential short-circuit it would have to reach its fusing temperature, assuming a frequency of 50, in something like 0·0005 sec. Assuming no cooling and a specific heat of 0·095, this would require a current having an R.M.S. value for the 0·0005 sec. of 14 500 amperes, which at 6 000 volts is many times greater than 6 000 kVA. Again, I do not see how the potential short-circuit of 100 000 amperes could be limited to 8 446 amperes as shown in Fig. 7. In Fig. 22 the author shows an oscillogram of a 400-ampere modern fuse successfully clearing a potential short-circuit of 100 000 amperes. The maximum current shown is 25 000 amperes, but approximately 5 cycles were occupied in clearing. This presumably shows that the element fused in something like 0·001 sec., thus introducing the limiting resistance of an arc, and that this arc persisted for 5 cycles. Why is the arc voltage 90° in advance of the current? In this case again it does not appear possible to fuse so early in the growth of a short-circuit. When, however, the load current is very small compared with the possible short-circuit current, and provided that the section of fuse wire is made as small as possible, I agree with the author that the wire will melt very early in the growth of the short-circuit. For a given metal, the time required to fuse is inversely proportional to the *square* of the current density and therefore there is a very great advantage in keeping the section at the smallest possible value. For potential-transformer fuses and the like, I advocate more attention being given to the supporting of the wire so as to permit the use of extremely fine wire. Referring to tests with limiting resistances, the author states that the maximum current was about 100 amperes, whereas without resistance it would have been 600 to 1 000 amperes, and he says that this tends to prove that rapid melting of the fuse is essential. The advantage of the resistance is not due to this; in fact, resistance will increase the time taken to fuse. The author claims that more consistent protection can be obtained with a fuse than with a circuit breaker, because the former has a thermal characteristic. A breaker can be provided with fused trips which will have a thermal characteristic. Moreover, these time-limit fuses can be so chosen as to give the desired time-lag, and for this reason a lead-tin alloy is generally used, whereas the design of a main fuse is determined by breaking-capacity considerations. Frequently, however, a fuse characteristic is considered quite unsuitable and in those cases a breaker lends itself to the addition of other time-delay devices. For dealing with small, normal loads there is certainly a field for high-tension and low-tension fuses, but I think that it would very seldom be good policy to install fuses for dealing with normal loads of 3 000 and 4 500 kW as is advocated in Table 3. A limiting resistance is of course only permissible when the normal load current is small. I prefer the fuse and resistance as separate items, as the former has to be renewed, whereas the latter should never require renewing. As the load current is always small in these cases, the fuses can be of very small section and therefore rapid in operation. The resistance is therefore only in circuit for an extremely small fraction of a second and there is no difficulty in designing one which will be of small dimensions, and which will

yet have no serious rise of temperature under short-circuit conditions.

Mr. W. Fennell: Air-break fuses are not referred to much in this paper, and one special type, viz. the "horn break" fuse, has not been mentioned. I think this type has some good points. The fuse, as used outdoor in Mid-Cheshire for controlling transformers up to 300 kVA at 33 000 volts, is enclosed in a glass tube about 2 ft. long provided with type-metal ends, and were supplied by Messrs. Metropolitan-Vickers. These are fixed in substantial clips, the fuse being horizontal. Horns are attached to the clips, so that when the fuse blows the glass is destroyed, the arc rises up the horns and goes out. The glass tube allows very thin fuse wire to be used by protecting it from birds and weather. I have tried these on "short circuit" and they have always worked satisfactorily. We have also some oil switch type fuses which have recently been designed by the New Switchgear Co., perhaps an improvement on those referred to in the paper. The fuse is fixed to contacts suspended on a rod passing through the lid. When the cover is closed a lever is operated externally, the fuse is lowered into the oil and engages with contacts fixed to the bottom of the case. There is a very simple locking gear which prevents the fuse contacts from engaging the live contacts until the cover is closed. I think this is a very convenient and safe form of fuse for controlling the small transformers. It has the advantages of a hand-operated oil switch as well as being free from the risk to which the types described in the paper expose the operator should the cover be thrown into contact position on a short-circuit. I have a rough-and-ready method of testing medium-pressure fuses which are submitted to me as being suitable for use on distributing mains, by connecting them through a massive switch to the leads close to a substation battery. There is practically no inductance in the circuit. Most of the fuse carriers explode in the way shown on some of the lantern slides exhibited by the author. In a number of cases the fuse terminals are burnt so badly that the carrier cannot be used again, and in other cases the whole assembly has been destroyed. The Aeroflex fuse under these conditions operated quietly, and the carrier was undamaged. I trust that the makers will consider bringing down the prices of Aeroflex fuses to a figure which will allow of their use. A drastic reduction in price would result in such a demand that manufacturing costs would be much lower than on the present small output, and the firm's total profits would increase.

Mr. N. E. North: Whilst such developments as Aeroflex fuses are certainly very interesting, are we on the right lines in making such developments which, in order to attain successful operation, make for a more complicated design? I feel that in the majority of applications the replaceable element feature of a fuse condemns it as being the ideal protective device. Should not the line of thought be to produce a safety interrupter which, either automatically or by hand operation, re-establishes the circuit? Some may say that cost will be the great objection to such a piece of apparatus, but if we refer to the catalogue prices of some of the newer and more elaborate fuses discussed, we certainly have a figure at which circuit-protecting devices of the type suggested could be manufactured. The design will doubtless have to be on entirely different lines from what we have previously experienced, and the circuit may have to be broken and established under conditions similar to those obtaining with the present alternatives in fuse construction. In making these remarks I have in mind industrial and household applications, because I feel that we should really divide the paper into two sections, and consider the fuse protection in connection with higher voltages and currents separately. I cannot agree with the author when he talks of the rupturing force of a fuse being the product of the current and the voltage. I think that most of us will agree that, quite apart from insulation considerations, the effect of rupturing, say, 5 000 volts at 5 amperes is quite different from that of rupturing 5 000 amperes at 5 volts. Moreover, the character of the circuit, i.e. whether it is inductive or not, is of major importance. In speaking of the high-powered fuse, we must remember that to rupture the circuit quietly and in the quickest possible manner, is not always ideal or good for the circuit which we are protecting. Experience with magnetic blow-out fuses has led us to reduce considerably the magnetic density in certain traction applications. Moreover, there are numerous cases, particularly at higher d.c. voltages, when it is essential to open the circuit in stages, the blowing of each succeeding fuse inserting greater resistance prior to the last fuse finally opening the circuit under small-current conditions. For this reason I must support the author and disagree with Mr. Hope when he complains that the Aeroflex fuse should come next to the oil fuse on the author's chart. Mr. Hope says that it is essential to exclude all the air for satisfactory operation, but tests which I have made on air fuses, using wire strand, prove that they can be entirely satisfactory (and it is much simpler to replace the element), provided that the fuse is designed to deal with the conditions which arise as a result of the expansion of the gases and surrounding atmospheres, and provided also that suitable cooling and expansion devices are incorporated in the design of such a fuse. Fuses of this type are in satisfactory operation on recent 3 000-volt d.c. traction schemes. I suggest that the value of the paper would have been slightly increased if the periodicity of the circuits shown on the oscillograph records had been given.

Mr. J. D. Peattie (*communicated*): The author has cleared up many misconceptions regarding the phenomena accompanying the operation of fusible cut-outs. It would have added to the value of the paper if he had extended his arguments a little further, and tackled the definition of "rupturing capacity" itself. A great deal of the uncertainty of the whole matter seems to originate in the definition and use of the term "rupturing capacity." It is by no means clear what relation the number (which incidentally has no direct physical significance) defined by the B.E.S.A. specification as "rupturing capacity" bears to the actual physical phenomena inside the circuit-breaking appliance during the interruption of the circuit. The way in which it is generally used, coupled with the introduction of constants applicable only to steady conditions, tends to obscure

the fact that, for the most part, transient phenomena are involved. It seems to me that four main factors are involved. On the one hand, we have the energy which is liable to be released at the circuit-breaking appliance and the rate at which that energy can be released, and, on the other hand, we have the amount of energy which can be absorbed by the circuit-breaking appliance and the rate at which it can be absorbed. The satisfactory operation of the appliance depends on the balance between these factors. The author deals with the last two, but is somewhat vague in his references to the first two. In this connection, it must be remembered that the energy is derived from two sources. One, the more important in transient phenomena, is the store of energy —electrical, magnetic, mechanical and otherwise—in the system itself, and the other the prime mover which is continually replenishing that store and maintaining the potential of the system. I think, therefore, that it will be necessary to extend the definition of rupturing capacity to cover the question of energy absorption or dissipation, and also to introduce the time element. In the meantime, the quantity defined as "rupturing capacity" does not appear to provide a full specification, any more than the product of open-circuit volts and short-circuit amperes would provide a complete specification of the capacity of a generating set. In Fig. 36 the author gives rupturing capacities in kW,* but I suggest that kVA is a more suitable term. I also notice that he frequently refers to short-circuit powers of so many kVA. I think that the word "power" should, as far as possible, be restricted to denote rate of change of energy, especially in considering this particular question, where much of the existing confusion arises from the use of numbers having no physical significance as a measure of actual physical quantities, such as energy or rate of change of energy.

[The author's reply to this discussion will be found on page 954.]

* Since corrected.

North-Eastern Centre, at Newcastle, 22 March, 1926.

Mr. P. G. Ashley: The paper is particularly appropriate at the present time when the prospect of a considerable increase in electrical supply is contemplated in accordance with the scheme recently outlined by the Government. If such a scheme is put into operation we may anticipate that a primary transmission system operating probably as high as 132 000 volts would be erected with secondary systems at 66 000 and 33 000 volts. Main tapping points, and tapping points where the consumption of energy was large, would probably be controlled by outdoor type oil-immersed circuit breakers, but on the secondary systems at small tapping points where the monetary return from the energy consumed was not sufficient to justify the installation of oil circuit breakers, another cheaper type of apparatus would be required. It would therefore appear that there will be a demand for apparatus capable of controlling energy supply at high voltages with low current rating and with a high rupturing capacity. The author has shown that two forms of such apparatus are available—the metal-clad oil-immersed switch fuse, and the resistance-type fuse with spring tension. Both these pieces of apparatus are simple and can apparently be made more cheaply than an oil circuit breaker for the same duty, and the author has shown that they are reliable under short-circuit. The resistance type of cut-out illustrated in Fig. 37 is very interesting, particularly in view of the satisfactory operation of this cut-out on short-circuit as shown by the author. The cut-out seems to be very similar to the liquid-filled high-voltage cut-outs which have been on the market several years and which are extensively used in America. The main difference is that the author embodies his limiting resistance in the spring, whereas with the other type of cut-out the limiting resistance is external to the fuse itself. The idea of embodying the resistance in the fuse is not new. One very good form of resistance cut-out, of which thousands are at present in service, employs a very fine-gauge resistance wire, wound spirally on an insulating core, the whole being embedded in marble dust. The spiral construction enables a long wire to be used in a small space, and short-circuit tests on this cut-out in comparison with an exactly similar construction, using oil in place of marble dust, showed that the latter was more effective in quenching the arc. These short-circuit tests also showed that for satisfactory service the value of the resistance could be as low as 3 ohms per 1 000 volts and that under all conditions this was quite satisfactory. American engineers in general recommend 4·5 ohms per 1 000 volts, although I believe that in one type of cut-out the actual value was found to be only 0·3 ohm per 1 000 volts. One inherent difficulty with the cut-out illustrated in Fig. 37 would appear to be that of satisfactorily combining the resistance with the spring. Assuming the figure previously given of 3 ohms per 1 000 volts, the spring would need to have a resistance of about 400 ohms for a 132-kV cut-out. There would appear to be considerable difficulty in obtaining this, while also retaining the resilient characteristics of the spring. I should therefore like to ask the author what value of resistance he recommends for his fuse, and how he proposes to embody this resistance without weakening the spring. It is gratifying to note that the troubles experienced with the early copper fuse wires in oil have now been overcome by adopting bi-metal fuse wires. These early troubles were very disconcerting and one suggested method of overcoming them was to use an oil having a very low sludge value, as it was thought that the action was equivalent to carrying out a sludge test on the oil. This was disproved when results were available on a series of tests with different classes of oil. A copper fuse wire of a definite size was loaded with its normal full-load current for long periods in different grades of oil and it was seen that the oxidizing effect was practically constant and did not appear to be a function of the sludge value of the oil. The author suggests that the improvement which was effected by

adopting bi-metal fuse wires in place of copper was due to the increased radiation surface obtained. This theory is confirmed by the fact that a similar improvement has been obtained by using copper fuse wires threaded with closely-fitting glass tubes. This device entirely prevents oxidation troubles, but it is not sufficiently robust for apparatus which may receive rough handling. Table 15 of Report E/T23 published by the British Electrical and Allied Industries Research Association, gives interesting figures in regard to the relative action of various catalysts. In this table it is shown that the catalytic action of lead is almost exactly the same as that of copper, and that zinc has an action

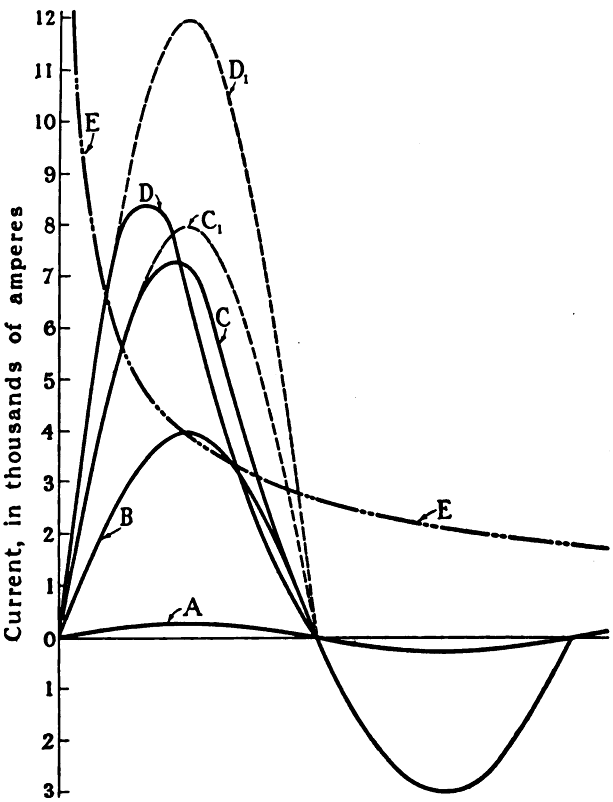

Fig. G.—Inherent current-limiting effect. Copper fuse-wire in oil.

only slightly less. The bi-metal employed being an alloy of lead and zinc, it will be seen that there is very little difference between the catalytic action of this metal and that of the copper previously used. For this reason I cannot agree with the author that the prevention of oxidation was due to the substitution of a non-catalytic agent for copper. Reference is made in the paper to the limiting effect of a fuse on short-circuit. This is particularly interesting as it is a point which is not often realized by users of fusible cut-outs. This phenomenon is mentioned on page 922, but it might be of interest to show a diagram which may be used to illustrate the point further. In preparing this diagram (Fig. G) no attempt has been made to draw the curves very accurately, as it is intended purely as an illustration. The heat generated in a fusible element when carrying current is proportional to I^2R. Normally this heat is dissipated by conduction, convection and radiation, but under short-circuit conditions the time of current-flow is so small that these dissipating factors become ineffective. We may therefore assume that all the heat imparted to the element is absorbed in increasing its temperature. If the short-circuit occurs at zero value of the normal current wave, the expression for the short-circuit wave becomes $I_0 \sin pt$ and the heat generated is proportional to $\int_0^t R(I_0 \sin pt)^2\, dt$, which on integration gives the expression $RI_0^2(\frac{1}{2}t - \frac{1}{4p}\sin 2pt)$. For any given element there is a definite value of heat which will raise its temperature above the melting point and cause it to volatilize. The expression $RI_0^2(\frac{1}{2}t - \frac{1}{4p}\sin 2pt)$ can therefore be equated to a constant. If the values of current and time which satisfy this equation are plotted, a rectangular hyperbola is obtained which is shown at E in Fig. G. This curve becomes asymptotic at a current value equal to the minimum fusing current of the element, but the equation given above does not hold over the whole range of time, owing to the complicated factors introduced by dissipation of heat. Curve A is the current wave which, if prolonged for 7 or 8 minutes, will cause the fuse element to blow. Curve B is an actual short-circuit current wave taken when this copper fuse wire was subjected to a short-circuit from a 6 000-volt turbo-alternator. The kVA value of the short-circuit was in this case limited by the size of the machine and the series impedance. Curve C_1 shows a hypothetical short-circuit current wave, assuming the cut-out to be used on a system where the available short-circuit corresponds to the value shown for the peak of the curve C_1; in other words, at a place where the potential short-circuit is 8 000 amperes. Actually, the fuse will not rupture this kVA, as a limit is introduced by what we may call the inherent current-limiting effect. As the value of the current increases from zero, as shown by curve C_1, at a certain time, the current rises to such a value that the heat generated is sufficient to melt the fuse and to volatilize it. The metal vapour which replaces the fuse element is still capable of supporting an arc, and the current therefore continues to increase with time until the arc becomes unstable; in other words, the volatilization of the element prevents the current from increasing to the value which the constants of the system would otherwise allow. Curves D_1 and D illustrate the same effect for a position where the available short-circuit or the "potential" short-circuit is greater than in the case of C_1. The practical effect of this phenomenon is that the short-circuit kVA rupturing capacity of a fuse link is fundamentally dependent upon its section and material, in relation to the available short-circuit; and if this phenomenon is to be utilized in service the relationship between these factors must be carefully considered and adjusted. It would therefore appear desirable that the curve shown by the author in Fig. 3 should have kVA plotted against minimum fusing current rather than current-carrying

capacity,* since the limiting effect and also the current-carrying capacity, is dependent upon the minimum fusing current.

Mr. H. W. Clothier: The predominating feature of all satisfactory designs of circuit-breaking devices appears to be the mechanical strength of the enclosure. It was the feature lacking in the early Ferranti oil-break fuses. The cartridge fuse shown in Fig. 4 has a double enclosure of strong fibrous tubing. This has more to do with its high short-circuit breaking capacity than the low fusing-current/load-current ratio, or any other constructional feature. A comparison of tensile strength of the several materials recorded in Table 1 would be of interest, and might to advantage be added if the author has available records. I understand that the "bakelized fibre tube" which has the lowest absorption test is similar to material known as "bakelite dielects," a form of wound paper compressed in a split mould after winding. The author has drawn attention to the important difference between the maximum energy which might pass through a short-circuit as determined from its location on a system, and the actual energy of the circuit broken by a fuse which intercepts it, the fuse having a current-limiting characteristic. An extreme case in practice is a fuse on a potential-transformer circuit. A fuse having a comparatively small breaking capacity can be used on a power station switchboard alongside of main circuit breakers of very large breaking capacity. When acting on heavy short-circuit the fuse has a very much shorter time-lag than a circuit breaker; it may break circuit on the first wave of a short-circuit and before the current reaches the maximum that it would attain through a circuit breaker in a corresponding location. Thus an oil-break fuse may be of lighter construction than a circuit breaker in the same vicinity. This is one factor leading to economy in the use of the oil-break switch-fuse, and it is just possible that it might be applied for linking up sections on large bulk supplies where the current-limiting ability might be used as a substitute for reactances.

* Since corrected.

Mr. Vernon Hope also took part in the Newcastle discussion. The substance of his contribution to the discussion is contained in his remarks in the discussion before the Institution (see page 945).

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, MANCHESTER AND NEWCASTLE.

Mr. L. C. Grant (*in reply*): Before attempting to reply in detail to the remarks of those who took part in the discussions, I would point out once more what I have said in the paper and emphasized at the meetings, namely, that the paper is intended to deal with rupturing capacity and the factors having an immediate bearing upon it. It has been said, for instance, that I have not dealt with certain time and current ratings: these and some other subjects mentioned are outside the scope of the paper, but I would mention, in passing, that I have been investigating the question of rating, and am inclining more and more to the belief that such arbitrary ratings are of little value and the really important things are (1) the minimum fusing current, which can be obtained definitely in practice on a properly calibrated cut-out, (2) the ratio of maximum or sustained full-load current to minimum fusing current, and (3) the full rating characteristics of the cut-out, which I consider can be obtained only from an accurately produced time/current curve.

Another point which has been brought up by one or two speakers is the question of the degree of goodness or badness of a given cut-out. I am afraid that I am sufficiently exacting to recognize as good only one class of cut-out. I consider it to be a satisfactory circuit-breaker only when it interrupts its maximum rated short-circuit current without developing any symptoms such as flashing or burning, or even excessive noise, and certainly without causing any damage whatever to the container or surrounding apparatus. Therefore, while I appreciate the reasons underlying Mr. Gregory's plea that it is sometimes sound engineering to use low breaking capacity cut-outs even though they may be blown to pieces when attempting to clear a fault, I would point out that a performance of this class can be simulated and possibly improved upon by the simple expedient pointed out in the paper, i.e. that of using an open wire strung between terminals and without any enclosure. Inexpensive apparatus is essential in the development of economical rural schemes, but if a cut-out worthy of the name is required, it is possible nowadays to obtain one which is a good circuit-breaker at a cost comparable with that of cut-outs which are such in name only.

With regard to Mr. Gregory's closing remarks, I agree with him that the subject of fusible cut-out design and discrimination is worthy of continued research. Properly conceived, a fusible cut-out is a scientific and reliable piece of apparatus; in some respects, perhaps, more so than an oil circuit-breaker.

I agree with Mr. Morgan's remarks with regard to nomenclature and have endeavoured to embody standard terms as far as possible, but I would point out that the standardization of terms used in fusible cut-out work has not yet been settled definitely, consequently, it is not possible to use standard nomenclature, except up to a point. As Mr. Morgan himself states, the nomenclature of the subject is at present under consideration by the Editing Committee of the B.E.S.A., and the recommendations may be adopted as standards in the near future. With regard to Mr. Morgan's remarks on the failure of fuses, he states that it appears to be necessary to find out exactly what is meant by failure. I have already endeavoured to define what I mean by successful operation, and I do not agree to the American Bureau of Standards 1916 Catalogue of types of failure being used in any way except to *describe* the type of failure. The cataloguing of failures in this way seems to imply that certain types of failure may be recognized as successful operation. I maintain that if a cut-out is properly designed—and it can be done—there will be no need to discriminate between such failures as, for instance,

rupturing of the cartridge, blowing off of the caps or ends, ignition of cotton placed around the cartridge, remaking of the circuit after it has once been opened and so on. I would suggest that any engineer who considers that such failures may be forgiven should place himself in the vicinity of a cut-out when it is operating in such a fashion.

With regard to the comparative performance of a fusible cut-out on alternating current and direct current, I have carried out a number of comparative tests of this nature and have not discovered any material difference in the performance. Furthermore, if the cut-out is properly designed and correctly applied to its duty, it should, under fault conditions, operate on the initial rising-current curve, the rate of rise of which depends on the time-constant of the circuit and not on whether the supply is from a battery or an alternator, etc. There is certainly a difference in the inductance of the circuit with direct as compared with alternating current, but there should be no difference in the performance of the cut-out. I am not endeavouring to lay down difficult or impossible conditions or to theorize without foundation; it has been my experience that a properly designed fusible cut-out will operate equally well on alternating and direct current, with no noticeable difference in its performance. There seems to be a great deal of misapprehension about the theory of interrupting circuits and about the performance of cut-outs and circuit-breakers, and there seems to have been a lamentable amount of misdirected effort; so much so, that when I first set out to investigate fusible cut-outs I wondered if what appeared to be hard facts had in reality been refuted at some previous time and had resulted in some of the curious views held on the subject of fusible cut-outs.

Mr. Clothier repeats in substance Mr. Gregory's perhaps weak support of the defectively designed cut-out, when he states that the cut-out is a renewable part and not very expensive, and consequently, if it does its primary function of isolating the fault, it may be pardoned if, in the process, its condition becomes such as to fit it only for the scrap-heap. My reply to this and to Mr. Gregory's remarks is that this is not the performance of a fusible cut-out at all, and an incomparably better performance could be obtained by a properly designed cut-out at little if any extra cost. I am glad that Mr. Clothier is with me in looking forward to the time when we shall endeavour to obtain the isolation of a fault without either pyrotechnical displays or secondary damage. The question of the ratio of actual power broken to "potential short-circuit power" is, of course, vitally important, and I can assure Mr. Clothier that the ratio of 1 to 1·2 is quite practical and is obtained with safety and simplicity. I do not, however, agree with Mr. Clothier that so sensitive a margin, as he terms it, may be likely to cause trouble, and his comparison with the relay protected gear is, I think, in some respects a false one. The integration of time and current, which is basic in the performance of a fusible cut-out, is absent in the usual protective relay arrangement, and it is possible to take advantage of the time/current curve to a remarkable extent. I agree that purely a current setting of such a ratio would indeed be a bad thing. I am afraid that I do not see the argument for a thermostatic relay in the place of a fusible cut-out when the latter provides the thermostatic device and the circuit-breaker in one.

Mr. Clothier raises the same question—although in a different sense—as Mr. Morgan, i.e. nomenclature. I agree that the word fuse "trips lightly from the tongue" and that "switch-fuse" for instance is a very descriptive term, whereas "oil-immersed fusible cut-out" is clumsy, but our Standardization Committees agree upon these terms and are always ready to criticize an offender. Various types of pressure indicator were used in the tests, and I think that Mr. Clothier has seen at least one of them. Two of the impulse type which were tried utilized a lead or copper anvil screwed to the fuse container and gave quite good results. A third was a device which combined the functions of electrostatic condenser and contact-making device. This was calibrated hydraulically and gave results comparable with the others. Another device was a small high-speed engine indicator modified for the tests. It was thought at first that the inertia of the moving parts of this would be such that no useful results would be obtained, but the figures which were obtained have been comparable with the results obtained with the other devices mentioned and with other apparatus which I have seen used for this purpose.

With regard to Mr. Hooker's remarks, the fusible cut-out is, of course, very suitable for controlling rural supplies. The cut-out he mentions has been tested and is duly dealt with in the paper, and I cannot add anything useful to the information therein given. With regard to the suggestion to use silica instead of glass, silica is similar in some respects to glass in its characteristics, except that it is possible to make thicker containers and so obtain increased mechanical strength in that way. Transparent silica, however, is rather expensive, and if used for fusible cut-out work it will probably be of the opaque variety. I have tested many types of liquid filling for fuses and have not yet found one which in any way reduces the energy or explosion set up in interrupting the circuit, or is in any way an advantage over switch oil or, for that matter, pure water.

With regard to Mr. Dunsheath's opening remarks, I have endeavoured to give in the schedule of tests a useful description of some of the cut-outs tested and have indicated whether they are useful or otherwise. This, together with the remarks in another part of the paper wherein the requirements of a good cut-out are set out and wherein the performance of a bad one is described, are surely definite conclusions. I have already made some observations on the question of nomenclature and fundamentals, and later refer again to them, so that I will make no further reference here. Mr. Dunsheath's remarks with regard to the discrepancy between load-current/fusing-current ratio and fusing-current/load-current ratio refer to a typographical slip —since corrected. With regard to Mr. Dunsheath's and another speaker's methods of showing the effect of altering the ratio, there are several ways of doing this and I considered using a somewhat similar alternative to the curve showing the power actually interrupted, but decided on the latter, which, I hope, is a more effec-

tive way of demonstrating the point so that he who runs may read.

Mr. Dunsheath's second point is interesting, but I do not think that I am guilty of the omission he mentions. There is shown in the paper an oscillograph record and a description of tests on a cut-out similar to that he mentions. The principle has been tried quite extensively, and some of the very latest tests which I carried out before completing the paper were bearing on this very point. In practice, it is extremely difficult to design a container capable of withstanding a useful pressure. Again, there is the difficulty of developing this cut-out to any size, as mentioned by Mr. Hope and Mr. Brazil. This is an apparently insurmountable obstacle and in the design and rating of fusible cut-outs is a fundamental problem which must be overcome equally with that of obtaining high rupturing capacity. Thirdly, a cut-out of this pattern operates with a display of phenomena which I consider to be undesirable and quite unnecessary, and which would be considerably augmented if the 2 000 kW mentioned by Mr. Dunsheath were raised to anything like 50 000 kW, as used in the tests described in the paper.

The silk-ribbon element which Mr. Hope describes is of the resistance type and its performance depends, at any rate to some extent, on the resistance embodied in the fusible element itself. With regard to Mr. Hope's remarks on pressure set up, apparently there is something wrong with his figure of 100 tons to the square inch. I quite agree with him that what is really needed is a liquid which will damp out any explosion without setting up any secondary pressure.

Mr. Isenthal states truly that silver is a good material to use, but I do not think that the material of the element would appreciably help the rupturing performance of a tubular cut-out of the open type to which, I take it, he refers.

With regard to Mr. Scott Maxwell's remarks, I would again emphasize the point that the manner in which a cut-out clears a fault is of great importance—I mean whether it does it properly or otherwise. Again, I consider that even one failure out of eight tests, as in the tests of the Duquesne Lighting Company, is avoidable if the cut-out is operating consistently. The further tests to which he refers and which I carried out during 1922—and subsequently to this date—are shown in Table B, which refers to six tests on cut-outs rated at 6 000 volts. It will be noted that there were two failures out of six tests, these two failures taking place at the rated voltage of the cut-out. The four remaining tests were carried out below the rated voltage of the cut-outs. I agree, to some extent, with his remarks that the higher the voltage, the higher will be the kVA rupturing capacity. This is substantially true of most circuit-opening apparatus, and the Duquesne tests tend to show that the performance on higher voltages may be somewhat better than on lower voltages. I think that Mr. Scott Maxwell is perhaps treading on rather dangerous ground when he commences to discuss pressures. There are pressures of different natures, as we know, and the fact that the end disc is blown off at, say, a pressure of 50 lb. per square inch may not prevent the pressure rising to very much higher values than this. The nozzle effect alone is sufficient to produce such a condition, while the behaviour of a steep pressure wave is very peculiar indeed and, I think, it can safely be said is not thoroughly understood. I have known instances where a strong material was entirely destroyed during the rupturing of a circuit, while a very much weaker material in a similar position was entirely untouched. An instance of such a vagary occurs to me. An explosion due to a high-tension breakdown took place in a large power station. A window frame was lifted completely from its fastenings and deposited some distance away while the glass panes remained intact. I think that while we have instances of this sort it is as well to proceed cautiously when considering explosion pressures.

If I read them correctly, Mr. Rudkin's opening remarks seem rather confused. He appears to be mixing two ideas. I quite agree that for rupturing capacity as high as 50 000 kVA the oil-immersed circuit-breaker is a more convenient piece of apparatus to use, but it is also a much more expensive piece of apparatus and the oil fuses costs less than half that of a corresponding oil circuit-breaker. I note that Mr. Rudkin objects to my conclusions that no suitable porcelain fuse-carrier can be made. I am interested to hear that he would not hesitate to design air-break cut-outs of the porcelain-carrier type for 30 000 kVA at 15 000 volts. It has been sufficiently demonstrated that high powers can be broken by a simple wire in air and, providing sufficient space is allowed, this can be done quite reliably. The effect of enclosing a plain fusible element in a porcelain or other carrier is to make it into something comparable with a bomb. Neither this nor a plain element in air forms an efficient cut-out, for the reasons enlarged upon in the paper. I am aware of most of the deficiencies of fusible cut-outs, but I do not think that cost is one of them when the latter is compared with the alternative circuit-breakers. Spare elements are of nominal cost in the fusible cut-out to which he refers, as common fuse wire is used for that purpose. The delay in restoring service is, of course, one of the deficiencies which must be taken as part of the price to be paid when the cost of an oil circuit-breaker cannot be borne by the job. Experiences cited in the paper, which are examples of everyday practice, bear out the assertion that 50 000–70 000 kVA is a short-circuit power to be met in a large proportion of present-day installations. For pressures above 3 000 volts experience on high-power systems has shown that at least 50 000 kVA has to be handled except on the most remote portions of the system and small secondary networks.

With regard to Mr. Rudkin's closing remarks, many small supplies have to be taken from comparatively high-power lines where the short-circuit power is certainly of the order which I have indicated and where the revenue to be derived from the small supplies is so small that a circuit-breaker is economically impossible. If the term "radiation" refers to oxidation—apparently resulting from surface voltage-gradient—I think this has been covered by the paper. I do not think that there is much chance in practice of the respective cases for fuses and protective apparatus being confused.

MANCHESTER.

I agree with Mr. Hope that the cartridge cut-outs to which he refers were not broken down in the tests, therefore it is legitimate to assume that the breaking capacity is something over the figures given. His remarks regarding oil cut-outs require, I think, some qualification. The results were derived from tests, with one exception, namely, those for the high-pressure oil cut-out and, as I have said in the paper, the latter results were obtained by comparison with oil switches of similar dimensions which are known to have performed similar duty. Referring to pressure in oil-immersed cut-outs, it should be noted that although the pressures in oil containers may rise to high values, the commercial form of the oil-immersed cut-out is so designed that the container and other parts are able to withstand the pressures set up. I endorse Mr. Hope's closing remarks to the effect that the ordinary commercial fusible cut-out produced to-day is apparently designed without any knowledge of the subject, and that the time has come when designers will have to pay a great deal more attention to research if fuses are to be produced with reasonably high rupturing capacity. The information for which Mr. Mellonie asks can be obtained from Fig. 1. This chart was not made from any particular ratio of load-current/fusing-current. Assume, for instance, that one has a cut-out of 100 amperes carrying capacity. If this be wired for a ratio of 1 to 1·2, it will become a 120-ampere cut-out. If, on the other hand, it be designed for a ratio of 1 to 2, it becomes one of 200 amperes, and so on. I agree with Mr. Mellonie that the most economical arrangement for low-power circuits seems to be the use of a simple cut-out with a series resistance, but I do not agree with him that a highly rated resistance may be used or that the resistance may be allowed to become red hot for a fraction of a second. The emission of a hot gas is likely to cause a flash-over in adjacent high-tension apparatus, and it is known that trouble has been caused in this way. Toward the end of his remarks, Mr. Mellonie suggests that the sudden increase in temperature of the mass of the spiral in the resistance cut-out shown in Fig. 37 may produce oil pressures which are absent when the resistance is air-cooled and the cut-out a separate piece of apparatus. This was anticipated and provided for in the original design. Mr. Mellonie and other speakers have perhaps not entirely understood my suggestion that small fusible elements should be arranged to break the circuit on the initial rising-current curve. I think it is stated without ambiguity in the paper that "a feature found to be common to small cut-outs is shown perfectly by these tests, i.e. either the circuit is interrupted in the first half-cycle with extremely low arc energy, indicating good operation, or, in the event of failure of this rapid-extinction process, the arc persists or tends to grow, resulting very quickly in the destruction of the cut-out. . . . It appears to be the rule . . . that unless such light cut-outs can be designed to clear early in the first half-cycle, they will immediately be destroyed." A properly-designed rapidly-acting fuse is not assisted by the limiting resistance so far as current interrupted is concerned, but the resistance is a desirable second line of defence. The present value of the resistance, however, lies in controlling the current passed by the usual type of fuse employed, so that it is enabled to clear the relatively small current, whereas alone it would be incapable of clearing it. If a limiting resistance be used, the current cannot rise to a dangerous value, but the time taken for the cut-out to operate is obviously a function of the current value reached. This is illustrated, not refuted, by Mr. Mellonie's oscillograph record. The tables of tests and oscillograph records given in the paper show that some small cut-outs without limiting resistance operate on the rising-current curve. Clearly, if a limiting resistance is introduced it may be of such a value that insufficient current is passed to melt the fusible element in the first half-cycle, so that the limiting effect is absent, but the energy is kept by the resistance to a value which can be handled safely by the cut-out. This is bound up with the question of size of fusible element, and I would recommend Mr. Mellonie and others who took part in the discussion to consider the various points in their relation to one another.

I agree with Mr. Mallinson's remarks that it is only by full-scale experiments and a thorough analysis of all the factors involved that practical developments of any class of engineering can be obtained. There certainly exists the criticism which has been raised by other speakers as well, that the oil circuit-breaker provides greater switching flexibility than the fusible cut-out, particularly in the closing of the circuit. Also the replacement of the fusible elements takes a little time. These details will probably be overcome in part, and they are being dealt with in some apparatus. Of course we can hardly expect the fusible cut-out to develop the flexibility of the circuit-breaker. It is an intrinsically cheaper device and has limitations which must be paid for and which should be offset against the difference in price. Nevertheless, the possibilities of the efficient fusible cut-out are enormous and I hope that the situation has been cleared to some extent by the tests described in the paper. The cost of replacements are surely only nominal; they cost a fraction of a penny for the oil-immersed cut-out and a few pence only for the cartridge cut-out referred to by Mr. Mallinson. I think that Mr. Mallinson's further criticism has been met to some extent because there are designs wherein it is impossible to insert elements of incorrect rating, while the recharging of cartridges of any importance should be a matter for a responsible person, spare cartridges being carried to take the place of other cartridges while they are being rewired. I do not think Mr. Mallinson need be unduly perturbed about the massive construction to which he refers and which is more apparent than existent. The dimensions of the tank are, no doubt, responsible for this impression, but there is very little complication inside.

Mr. Burt's statement that a reduction in the quantity of metallic vapour will bring about an increase in breaking capacity is, of course, true and I think he will agree with me that reduction in the amount of metal melted in breaking the circuit is in effect the same thing as reducing the load-current/fusing-current ratio. In considering different materials it should be remembered that there are more factors than mass of metal

to take into account; the physical constants of the material used have an important bearing. There must be something wrong with Mr. Burt's calculations when he criticizes the result he refers to, namely, that the 120-ampere fuse would handle only about 6 000 kVA. He should remember that this curve is made up from test-results and is not based on calculations. He should remember also that there are more factors contributing to the melting of the fuse than the heat liberated in the portion volatilized. He has, apparently, not read my statements very carefully. He says he does not see how the "potential" short-circuit of 100 000 amperes can be limited to 8 446 amperes as shown in Fig. 7. It is clearly stated in the paper that Fig. 7 refers to a test at 180 volts on a transformer bank which at full voltage (440 R.M.S.) would give a maximum current of 100 000 amperes. It should be remembered that the illustrations are direct reproductions of the oscillograph records. Fig. 22 is not intended to show limiting effect; the test illustrates only the rupturing performance of this cut-out under rather a bad condition. This cut-out was not suitable for this purpose for two reasons: (*a*) it was too large, which is shown to some extent by exterpolating Fig. 3; and (*b*) the tests on this cut-out were carried out at 350 volts, whereas the full short-circuit current of the transformer bank was not obtained until the terminal pressure was raised to the normal value of 440 volts. I do not quite understand what Mr. Burt means when he asks why the voltage is 90° in advance of the current. The oscillograph record shows that the phase angle is constantly varying from approximately 90° lag until at the moment of clearance it is in phase. Mr. Burt's remarks with regard to limiting effect and limiting resistance has, I think, been dealt with in the reply to Mr. Mellonie's criticism. The case for the fused time-lag switch is usually defined, and so is the case for the fusible cut-out. In these days of hard finance it is unlikely that, in a properly managed system, there will be made mistakes such as the wrongful installation of a switch in place of a fusible cut-out, or vice versa, even for loads of the order of 3 000–4 500 kW. This is referred to again in another portion of my reply.

My chief criticism of Mr. Fennell's suggestion to use the horn break is that such a course is a reversion to the old type of air cut-out, which the tests have shown to be unreliable and dangerous. Mr. Fennell himself says that, when the fuse blows, the glass is destroyed and the arc rises up the horns and goes out. Given sufficient space, the most rudimentary apparatus will serve to clear a short-circuit, but the real problems are to clear without any outside phenomena or danger to other apparatus. I have carried out some tests on horn breaks and these are not at all reassuring. The arc across a horn break is an unreliable factor, it varies in its position and it varies to an extraordinary degree in length. Also, it is blown like a feather by the least puff of wind, and it requires an almost unbelievable amount of space if interference with adjoining apparatus is to be avoided. I am interested to hear that Mr. Fennell has been carrying out short-circuit tests on his own account, and to note that his results are similar to my own, namely, that most of the carriers explode and that the terminals are burnt and the carriers rendered useless, while accurately designed cut-outs operate quietly and without doing any damage.

I do not think Mr. North can divide up my paper into the sections he proposes. As stated in the introduction, I did not propose to enlarge upon the simple lighting or industrial power cut-out. The paper is obviously, I hope, intended primarily to deal with high powers. I do not consider the rupturing capacity of a cut-out or circuit-breaker to be the product of current and voltage, as Mr. North implies. I simply used this convention in dividing up the paper. The rupturing power of a fusible cut-out or circuit-breaker depends primarily upon the current passing through the arc, the voltage across the arc, and upon the time during which the arc is maintained. The product of the first two in properly designed apparatus is much less than the product of open-circuit voltage and short-circuit current, although there are instances where the design has been so bad that the product has been greater. The voltage across the arc is dependent upon many things, not only upon the open-circuit voltage as stated by Mr. North, but upon the type of break, the class of contacts, speed of break, timing of the arc, method of damping or immersion, and so on. This was touched upon to some extent in the remarks upon powder-filled and oil-filled cut-outs, but the subject is such a large one that it is impossible to go into it in detail in the present paper. I agree with Mr. North that it is not always good to rupture the arc in the quickest possible manner. This is definitely stated in the paper in the sections dealing with "Magnetic Blow-out" and "General Design of Ironclad Oil-Immersed Cut-out." It is stated in the latter section that tests were carried out with increased speeds—finally arranged for 40 ft. per second, as this gives the maximum speed of break without introducing the risk of pressure-rise. I do not think, however, it is necessary with a properly designed cut-out to open the circuit in stages, at any rate with such cut-outs as come within the scope of the paper. Such an arrangement is very complicated and cumbersome and in some installations where it has been installed it has been replaced with a single cut-out. The arrangement referred to by Mr. North, in addition to its complication, has the disadvantage that it operates disruptively and with risk of damage to the surroundings, and in the installation to which he refers was not considered entirely satisfactory. The periodicities of the circuits in which the tests were carried out were deleted from the advance copies of the paper through a misunderstanding but have since been re-inserted.

With regard to Mr. Peattie's remarks, the definition of "Rupturing Capacity" has occupied the attention of several committees for a number of years and even now is not satisfactorily determined. In the printed version of the paper, I have endeavoured to make clear what I mean by "rupturing capacity" in so far as it applies to fusible cut-outs. On the question of the energy liberated at the moment of rupture, I have endeavoured to deal with this—at any rate briefly in the paper—and Mr. Peattie should remember that the space allowable for the paper had to be allocated, as fairly as possible, between the different sections, and that the question of

arc energy and power is very complicated. It has been and is being investigated, but it is hardly possible, without becoming involved in a lengthy dissertation, to enlarge upon the point more than has been done in the paper. The transient effect is, I agree, very important: it will be found that there is a certain amount of information in the paper bearing on this point. The term "kVA" has been embodied in the final draft of the paper for the *Journal*.

Mr. Ashley remarks that the resistance cut-out described in the paper is very similar to the liquid-filled cut-outs so extensively used in America. I am afraid that I do not see the resemblance, nor do the Patent Office examiners. The principles and construction of the two are entirely different, while the tests described in the paper show that there is no comparison in the performance of the two. Again, I think he rather misses the point when he states that the idea of introducing the resistance in the fuse is not new. The undesirable features of the other form of resistance cut-out which he describes are that the whole of the resistance spiral forms the fusible element, which means that there is a large mass to be volatilized on short-circuit—an obviously undesirable state of affairs—and, secondly, there is a considerable length of heated wire in contact with marble dust, which results in an unstable combination. The long fuse element is not a desirable feature. Furthermore, I have pointed out in the paper that such a rudimentary marble-dust arrangement is not a reliable circuit-breaker. None of these objections are met with in the oil-immersed resistance-controlled cut-out referred to in the paper and mentioned by Mr. Ashley. The resistance cut-out referred to in the paper is a practical embodiment of up-to-date information. It has been exhaustively tested on short-circuit, while Mr. Ashley's fuse has been subject only to a solitary short-circuit. The tests described in the paper have shown that the figures he mentions for the ohmic value of limiting resistances are not safe. For the resistance of the 6 000-volt cut-out to which he refers, I would suggest a value of 30–50 ohms—preferably even higher—but I think that the most accurate way is to specify the current passed on dead short-circuit, as is recommended in the paper. I would also suggest that Mr. Ashley is in error in assuming that there is a linear connection between the voltage and value of limiting resistance required, and his conclusions with regard to the 132 kV cut-out referred to should therefore be made on a different basis for the two reasons first explained. The question of designing a suitable resistance for this fuse is surely one for the manufacturers of the fuse referred to. With regard to his further remarks, I would point out that the phrase to which he refers reads *in extenso* in the paper: "It was believed that the action was at least partly catalytic, but from the very mechanism of the action it was clear that catalytic action alone was not responsible. When copper wires were used it was found impossible to overcome the trouble while retaining a reasonable load/fusing-current ratio, and bi-metallic fusible elements having a copper core sheathed with tin or tin-lead were finally adopted. . . ."

DISCUSSION ON

"ELECTRO-FARMING, OR THE APPLICATIONS OF ELECTRICITY TO AGRICULTURE."*

THE AUTHOR'S REPLY TO THE DISCUSSION.

Mr. R. Borlase Matthews (*in reply*): On account of the fact that the paper has been discussed at a number of Centres, the various sections of the subject have been dealt with in parallel. However, as a matter of record, it is more useful to arrange the reply in the same serial order as that of the original paper; and this has therefore been done.

The discussions generally are indicative of the very real interest that is taken in this subject nowadays, while there is much useful constructive criticism. This constructive criticism follows two distinct lines: (1) It is suggested that experimental work should be undertaken to a much greater extent than has so far been done; and (2) there is a strong feeling in certain quarters that the whole problem is bound up with legislation, the view being held that the greatest hindrance to rural electrical development is obstructive legislation, sometimes national and sometimes local.

The experimental work, mentioned as necessary, is a recommendation which it is not difficult to make, but when it comes to working out the details, such as by whom this work is to be done, one comes up against the first great problem, namely, that the science of electro-farming appeals to, and should be of benefit to, two undoubtedly different classes of men—the engineer and the farmer. Mr. Atkinson states that the electrical manufacturers should finance research work, it being greatly to the advantage of the electrical industry that advance should be made, and his suggestion is endorsed by other speakers. In this connection, reference should be made to Mr. Wedmore's offer to put the resources of the Electrical Research Association at the disposal of this new science. On the other hand, there are signs that research work might be financed to a certain extent by farming interests.

Throughout the discussion it is observed that the traditional attitude, that the farmer is too conservative-minded to bother with electricity, does not apply to the farmer of to-day. Prof. Gilchrist is confident that experimental work on a large scale would meet with practical support from the branch of the National Farmers' Union in his district; and this opinion bears out the experience of other countries, where, as Mr. Francis stated in connection with Bavarian farmers, Farming Associations have been known to bear the expense of the distribution lines. It also appears throughout the discussion that experimental work has been spoken of, not merely as a necessity to discover in what way electricity can be applied to agriculture, but also as a means of convincing the farmer and the engineer of the practicability of the whole scheme. This is not surprising, for other countries are so much more advanced than ours in the matter of rural electrification, that there is no problem which has not already been tackled, as far as the engineering side is concerned; but on both sides conviction and steady purpose are lacking.

Mr. White raises the question of the suitability of wind-driven electric generators for the production of power for agricultural purposes. Such generators are certainly being used in this country and on the Continent, though not on a very large scale. The windmill can be used successfully for small lighting plants in isolated districts remote from any power scheme. Where electric power is required for driving a number of farm machines, the use of windmills is not to be recommended, on the score of capital investment, since the outlay on the batteries would be too great, especially where the winds are as uncertain as they are in such a country as Great Britain. Incidentally, in wind-swept countries like Denmark and Holland, electric motors operated from the public supplies are now being installed in the bases of many of the windmills.

Mr. Robson asks for more details with regard to the temporary tapping of 33 000-volt lines. It is customary on many parts of the Continent to do this for temporary thrashing and ploughing loads, using cables provided with special bare hook-ends having insulated handles. By means of the latter the hooks are simply hung on the lines and the transformer is thus connected to the circuit. In theory it may not appear safe, but in practice it works quite well. It must be borne in mind that there is never any load on the transformer when the connection is made; in fact, interlocking safety switches are often provided. An illustration of the connection to 30 000-volt lines of a 5 000-volt portable transformer for a 125-h.p. electric plough, at Versailles near Paris, is given in another paper by the author, entitled "Rural E.H.T. Distribution," mentioned in the Appendix on page 812. This work is, of course, only done by one of the electricians of the electricity supply undertaking.

Mr. Creedy and Mr. Minton raise the question of the different types of current. At present there is nothing more suitable and simple for the farmers' use than the three-phase squirrel-cage motor. Hence, for this purpose, a three-phase supply is favoured. Nearly all the farms at present supplied with electric current are on this system. The study of alternative methods of supply is a very fascinating subject, but there are so many other electro-farming problems to be solved, that the temptation at present is to follow the accepted lines of supply. Mr. Minton also asks if I have had any experience in laying tramlines over my farm. While there are none actually laid, they have been seriously considered. Two overhead ropeways have, however, been installed. At present, rails are only employed on farms where a considerable quantity of potatoes, sugar beet or sugar cane is grown. The fields are then usually connected to the factory by tramlines.

Mr. Anderson asks if the method of electro-silage cited in the paper prevents the considerable amount of

* Paper by Mr. R. Borlase Matthews (see p. 801).

waste which was experienced by the old method of merely applying pressure to the fodder. The answer to that is that it does, because the material is entirely enclosed and, except the top layer, is protected from the atmosphere.

Colonel Crompton refers to the industry of enriching the soil in Germany by producing nitrates from the air, and asks for further information. In addition to Germany, it is also a big industry in Norway. Large quantities of nitrates produced in this way are employed in this country. The manufacture can only be carried out on a large scale. I have investigated the process to see if it is feasible with water-power on my own farm, but I found it to be impracticable on such a small scale.

Mr. Turnbull raises a practical point in the wiring of cowsheds. He is thinking of devising a simple vulcanized-rubber system on porcelain cleats, as being preferable to steel tube. The latter is useless, unless protected by an impregnated hemp covering. Ordinary vulcanized rubber cable is not much better and, if employed, should be supported upon insulators as if it were a bare conductor. Reference should be made to the paragraph entitled " Wiring system " on page 805.

Apart from the purely engineering problems of supply, etc., interest in the paper centres chiefly around the questions of poultry-house lighting, intensive illumination for greenhouse plants, bee-house or apiary heating, ploughing and the treatment of crops.

Mr. Robson asks if mechanical milking is satisfactory, as a friend of his, an electrical engineer, once used it, but eventually gave it up. Like everything else, practical experience is necessary in the use of these machines, as I have found to my cost. Having gained that experience, they are most satisfactory. There is now no doubt about this; and one maker alone has 50 000 equipments in use to-day. There are over 19 000 installations of various makes in New Zealand. The reason that dissatisfaction is so frequently expressed with mechanical milking-machines is because it is not realized that such machines need special care, in properly cleaning and using them. Provided that such care be taken, it is no uncommon thing for grade A milk to be produced in dairies where mechanical milking is the rule.

Sir Daniel Hall evidently does not quite appreciate one economic side of the question, when he speaks of dairy farming. It is true that it does not matter whether any kind of a machine be driven by electricity or by hand, provided that both are equally efficient. The worker has yet to be found, however, who can separate 300 gallons of milk or yet churn 180 lb. of butter, as can be done by a machine using one unit of electricity at a cost of but a few pence.

Mr. Grant inquires if there is any recent information in regard to the economics of milk treatment by ultra-violet rays. So far the methods are only experimental, not having reached the commercial stage, though a plant of Dr. Lulofs's design is in use in Amsterdam.

Sir Daniel Hall is sceptical as to the financial advantage of electricity in poultry farming. If, however, the value of the extra eggs hatched and the extra chicks reared, plus the labour saved, is taken into account, the electrical method is cheaper. It is the overall costs that count. Electric light in the laying house means at least 15 per cent more eggs in the winter time, when prices are high, at a nominal cost for electricity.

Mr. Carter raises a more unusual point and arouses a different train of thought, when he suggests that the universal electrification of poultry farms would lead to universal lowering of prices and, consequently, the economic advantages detailed in the paper would not become a general advantage. It is no doubt true that if all poultry farmers were to adopt the lighting method at once, there would be a universal lowering of the price of the egg. This would naturally follow from the law of supply and demand. But all the poultry farmers in England together do not produce sufficient eggs for our own requirements. In fact, last year we imported 1 475 million eggs valued at £9 216 000, so that it would be necessary for the poultry farmers of other countries to adopt the lighting method on a large scale if the prices of eggs in this country were to be appreciably affected. We shall no doubt see the day when this practice will be universally adopted and eggs can be purchased at a standard price all the year round, since the cost of electric lighting for the whole season amounts only to about the value of one egg per bird per annum. By that time the poultry farmer who is enterprising enough to step in now will be taking advantage of some further new scientific practice to help lower his cost of production, such as applications of ultra-violet rays, in which interesting experimental work has already been done.

Mr. Moffett refers to the efficacy of the heating of poultry houses. Hens being of sub-tropical origin, it is more than probable that they would appreciate the comfort of extra warmth, although carried beyond a certain point it would render them liable to chills. It does not, however, seem to be an economical proposition, for it would probably be more profitable to increase the maize in the ration. The increase in egg production brought about by artificial lighting is not a matter of warmth or comfort. It is a feeding matter, the idea of which is to enable birds to have a longer day; instead of getting on to their perches at dusk, it provides them with additional time in which to scratch and feed.

In reply to Mr. Atkinson, who contends that I have been somewhat misled by the rate of growth of plants at night, the point is that, though of course it is fully realized that night is the normal time of growth, the growth under artificial conditions of intensive light has been expedited out of all comparison with normal greenhouse or hot-house growth.

Several speakers are interested in Mr. Sayers's idea for the warming of the soil by means of circulating the hot water from electricity generating stations in pipes through the soil, and the difficulties have been pointed out very thoroughly. There does not seem, however, any reason why such pipes should not be utilized, not under the ground but in greenhouses erected nearby. The heavy capital investment required is the chief objection. Mr. Owen D. Young, speaking in America, has made the suggestion that there should be closer co-operation between the farmer and the engineer, suggesting that each station should have its own agricultural department, and so it seems to be only

common sense that greenhouse cultivation should be a by-product industry of electricity generation.

A practical solution of one of the difficulties in the spread of electricity has been offered by Major Rich and others, in the suggestion that something should be done to reduce the retail prices of lamps. Certainly such a reduction would be of very great advantage. The average prices on the Continent are less than one-half of those that prevail in this country. Still the paradox exists that British lamps can be purchased here at similar prices if the buyer undertakes not to sell or use them in this country. The Electric Lamp Manufacturers' Association has assured me that they will reconsider the prices of lamps in this country in the coming autumn.

As might have been expected, the price of current is a point which the electricity supply engineers have seized upon, and their comments upon this and upon the legislative aspect of the question are decidedly enlightening. Mr. Carter is of the opinion that a farmer would prefer a fixed charge plus a low rate per unit, and he fears that the farmer would grudge the cost of electricity. The reply to this is that it is not so much a matter of the cost of the current as of the return which the farmer is to get out of it. Upon the Continent the farmer does not object to an average charge of 4d. per unit for power and 8d. for lighting, since any other form of power costs him much more. Inquiry upon the Continent has led to the conclusion that psychologically it is better to charge a low rate per unit, plus a fixed sum as a service charge, than to do away with service charges and make the rate per unit higher.

While the figures given in the paper on page 802 were intended rather as an indication of the enormous potential load that is represented by the farming industry, they have been taken rather more seriously by Mr. Jenkin and Mr. Heslop. The ultimate figures of 1 000 and 1 295 million units per annum respectively, that are the outcome of their calculations, exceed, however, my more moderate estimate of 800 million units. Still, the smallest of these figures represents an output that is well worthy of most serious attention.

During the discussions much has been heard concerning the sins of the Post Office, and the point of view of Post Office engineers has also been expressed. Above and beyond those difficulties, however, it does seem that until more helpful legislation than at present exists is put into force, the obstacles in the way of rural electrification in this country are unnecessarily large. Mr. Fennell's exposition of these difficulties might well be pondered upon by those who have influence in Parliamentary matters. It should, however, be pointed out that those engineers who have had the least experience in the construction of overhead lines find the greatest difficulty in complying with the existing regulations.

Another big question upon which a good deal of comment has been aroused is electrical ploughing. Sir Daniel Hall puts the case in a nutshell when he asks, "What prospect is there of doing the ploughing so much more economically by the application of electrical power that horses will be largely displaced ?" Already it is much cheaper than horses and has the advantage of being much quicker and more powerful, thus permitting better cropping. Electrical methods of harvesting and crop treatment will, however, have to be developed, as horses are largely kept for this purpose and therefore can also be economically employed for ploughing, though at the expense of the crops. On my farm of 600 acres there are only two horses; even these could be dispensed with if a light creeper track vehicle such as is at present on the market were substituted.

I was among those who had the good fortune to study under the late Prof. John Perry. It is interesting to call to mind one of the Professor's comments concerning the qualifications of an engineer. Among other things, he said, one of the most important qualities is imagination. Now this whole subject of electro-farming needs a very healthy imagination, for so much of it is in the future. It has often occurred to me that if I were to suppress a great deal of data of which I am fully aware, what a big case I could make out *against* electro-farming. I venture to suggest, therefore, that probably most of those who do not believe in its future as strongly as I do, possibly do not know as much about it as it has happened to be my good fortune to learn. Unfortunately, too many English people use their intellect to create difficulties, instead of to overcome them.

Agreement must be expressed with Mr. Montague Fordham and others who have spoken upon the subject of rural electrification, not from the engineering or agricultural point of view, but rather as a social problem taken in its broadest sense, which is what the whole question resolves itself into. At the same time the social situation is accompanied by most interesting engineering problems which are calling loudly for solution.

SOME NOTES ON THE EARTHING OF METAL OBJECTS OTHER THAN CONDUCTORS.*

By L. HENSHAW.

(*Paper received 7th January, 1926.*)

SUMMARY.

The importance of earthing metal bodies other than conductors is stressed by all electricity law-makers and is denied by few, if any, engineers. At the same time rules, regulations, etc., covering the installation and maintenance of electric plant and equipment strictly avoid specification beyond that vague expression "satisfactory." The paper suggests a starting point for investigation having as its objective the defining of conditions which will preclude all possibility of dispute.

This paper is the outcome of difficulties experienced in operating an Electricity Act under the existing divergence of opinion as to what conditions are essential to a satisfactory earth. The impossibility of developing a clear definition appears to increase in direct proportion to the amount of study applied to the subject. It seems possible, however, and very desirable, to include in all relevant enactments definite conditions with which an earth must comply before it can be declared to be satisfactory, such conditions being, of course, capable of relaxation by the enacting body. In countries in which electrical development is still in its infancy, and especially in those—and there are many—in which the popular mind is discursive rather than analytical, and agrarian rather than mechanical, such action is not only desirable but essential.

The author does not claim to have any special knowledge on this subject, and hence those who read this paper with the object of acquiring such information will be disappointed. Unfortunately, his time and facilities for conducting research are not commensurate with his inclination and field. The intention of the paper is, however, to encourage discussion on this most important question and, if the discussion so encouraged advances the issue of the specification referred to in the last paragraph of Regulation 127 in the Eighth Edition of the I.E.E. Regulations for the Electrical Equipment of Buildings, the author will deem his work well done.

The object of earthing metal objects other than conductors being to "ensure at all times an immediate discharge of electrical energy without danger," we may first consider the nature of the dangers contemplated. They appear to be shock and fire. In view of the small amount of current required to produce shock, and the fire-resisting properties of most conducting bodies, we may, for all practical purposes, assume that elimination of the former will include the latter. It is therefore necessary to provide equipment which will ensure at all times an immediate discharge of electrical energy without danger from shock. This is supposed to be carried out in practice by ensuring that, on the occurrence of a fault of a predetermined magnitude, sufficient current to operate the tripping device shall flow through the earthing system.

Let us now consider the path of the fault current and the obstacles it meets *en route*. Members are here referred to an interesting series of articles which appeared in the *Electrician* in 1915–16, beginning with Prof. Marchant's article in the issue of the 17th September, 1915. In these articles formulæ for the resistance of earth connections in terms of the resistivity of the soil and the nature, location and dimensions of the earth, are discussed at length. Much research has also been carried out and many valuable articles have been written on the nature and dimensions of earth-plates, rods and tubes and earthing leads.

The scope of this paper, however, is limited to consideration of the fault effects met with in general practice and against which protection from shock must be ensured; and we cannot, for obvious reasons, take into consideration the specific resistance of the various substances which lie between the neutral earthing equipment and every protective earth on the system. Omitting this and taking the simplest case—a 3-wire d.c. system with earthed neutral—our obstacles are composed of measurable resistances in series, collectively tending to restrict the flow of the fault current from the fault to the neutral point of the distributing system. Starting from the fault, they are :—

(1) the fault resistance,
(2) the resistance of the earthing leads,
(3) the resistance of the earth,
(4) the resistance of the neutral earth,
(5) the resistance of the neutral earthing leads,
(6) any resistance inserted between the neutral and earth.

Since it is necessary to guard against the occurrence of a dead earth, (1) may be omitted and, assuming the earthing leads to have been correctly designed and installed, (2) and (5) may be ignored. It has been argued that, in view of the probable existence in parallel of innumerable neutral earths of moderately low resistance, (4) and (6) should also be omitted from calculations, but the author sees no reason why a licensee or an owner who maintains, except at one point, the

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insulation of his neutral should be penalized in this respect or, conversely, why a premium should be put on poor maintenance. (It should be remembered that we are dealing with the earthing of metal objects *other than* conductors.) Hence we have three resistances in series, as shown in Fig. 1, in which B is the earthed body, r_1 represents the resistance of the earth connected to the metal body, r_2 the resistance of the neutral earth, and r_3 the neutral limiting resistance. Assuming a dead earth on B, the fault current will be limited to $E/(r_1 + r_2 + r_3)$, and this, irrespective of tripping or fusing values, is the maximum current with which the earthing system will be called upon to cope, even momentarily. Assuming that this current will be sufficient to operate the tripping device—we shall return to this point later—it is necessary now to decide whether the possibility of shock contact being coincident with the short period of time between the occurrence of the

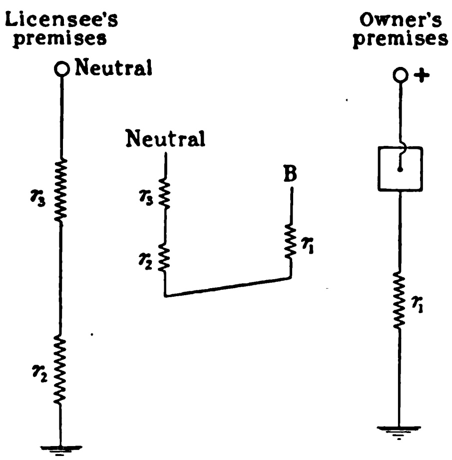

FIG. 1.

fault and the opening of the circuit should be taken into consideration, or whether the current required to open the circuit should form the basis of our calculations. There are, on record, instances of fatal accidents occurring during that period, and for this reason alone the author is of the opinion that the maximum current should be considered. The author's experience may be unfortunate—though by no means unique—but in his jurisdiction the majority of the plant operating on earthed systems relies for protection entirely upon its main fuses or breakers, and hence the circuit is not opened until a current equal to twice (or thereabouts) the full-load current is permitted to pass. Hence, in the case of plant of any magnitude, the value $r_1 + r_2 + r_3$ is required to be very low.

In the case most frequently met with, i.e. an owner's plant operating on a licensee's system, r_2 and r_3 are fixed by the latter, with the knowledge and approval of the licensing authority, and the owner is therefore able to control only r_1 in his earthing problems. And in the plains of India, in the dry season—say 9 months in the year—r_1 is most difficult and expensive and often impossible to maintain, and hence it is not surprising that the current of value $E/(r_1 + r_2 + r_3)$ is seldom sufficient to open the circuit. In fact, many attempts have, for experimental purposes, been made to open circuits by dead-earthing an outer conductor and these have, in spite of good earthing, met with success in only very rare instances.

In this connection it may be of interest to note an unusual case of fatal shock received from a stay wire. The licensee was not aware of the fault on the line, the pole was earthed and the stay wire was securely anchored in the ground. Apart from the pole and the stay wire there was no metallic path to the ground in the vicinity and the ground was dry. The stay wire was not directly connected to the earth wire but, the fault being on a cross-arm, it was obviously in good electrical contact with the pole. It is not known what the fault current was—the voltage across the outers was 440 a.c.—but apparently it was not high and yet, in spite of the nature of the ground, a fatal current was able to flow through the shock circuit. What are we to do about it? Are we to follow regrettable precedents and retard development by insisting that all earthing systems shall include costly protective devices? The answer to that, most emphatically, is not in the affirmative. "An immediate discharge of energy without danger." Discharge to what? Infinity? No, the sole object of earthing the neutral being to provide an adequate return for fault current we cannot get out of it that way. And we cannot compel an owner to fuse down to $E/(r_1 + r_2 + r_3)$. We can eliminate r_3 by shunting it with a light fuse, but we are not much better off, and certainly we cannot rely upon the manual opening of the circuit immediately this fuse blows and the circuit being kept open until the fault is cleared. Nor can we penalize a licensee by making him shut down, even temporarily, a section of his system on account of a fault on a consumer's premises. The author regrets that he has no solution of this problem. If he had, this paper would not have been written, since its object is to obtain information.

It will be obvious, however, that the maximum current which may—or should—flow through the earthing equipment is a most important factor in our problems concerning the earthing of metal bodies other than conductors, and hence it is necessary first to develop rules for its computation. And then, having decided by what means the fault is to be made known and isolated without detriment to other consumers on the same distribution, we may pass on to the consideration of the shock risks due to that maximum fault current.

We have so far dealt with the earth circuit, but our object, it must be remembered, it not only to discover faults but also to prevent those faults from causing harm to animal life. In this sense the earthing system may be looked upon as an *added* circuit for the purpose of taking from an *existing* circuit—the shock circuit—sufficient current to render the latter innocuous. In other words, the function of the earthing system is to eliminate, or at least to limit, leakage current in undesirable directions. It is therefore incident to the shock circuit and should be treated as such.

Acceptance of this view demands consideration of a

circuit which divides into two branches and unites again, one branch being the earthing system and the other a combination of a body touching the earthed member and the medium between that body and earth—the reuniting medium being earth. Our indisputable aim is to eliminate shock from the latter. Let us consider how our object can be attained.

Referring to the circuit diagram in Fig. 2, B is the earthed member and Y is the resistance between the earthing system and earth. Let us use y as the value of this resistance—usually the only test applied. Neglecting the resistance of the leads, this forms the total resistance of that side of the circuit. On the other side, K is the contact-making body the resistance of which is k, and X is the medium between that body and earth, the resistance of which we will denote by x. For all practical purposes the resistance of the two contacts may be included in k.

Assuming for a moment that k is a constant, it will be obvious that shock varies inversely to the value of x/y or, in other words, the greater x is with respect to y the less the shock will be. x and y therefore demand attention. Let us again refer to Fig. 2.

If I = maximum leakage current,

I_y = current in y,

and I_{k+x} = current in K and X,

then
$$I = I_y + I_{k+x} \quad \ldots \ldots \quad (1)$$

and
$$\frac{I_{k+x}}{I_y} = \frac{y}{k+x} \quad \ldots \ldots \quad (2)$$

Now let us assume the maximum current permissible through the contact-making body to be t amperes, then from (1) we get

$$I = I_y + t$$

or
$$I_y = I - t \quad \ldots \ldots \quad (3)$$

and substituting in (2) we get

$$\frac{t}{I-t} = \frac{y}{k+x} \quad \ldots \ldots \quad (4)$$

or
$$y = \frac{t(k+x)}{I-t} \quad \ldots \ldots \quad (5)$$

and for safety
$$y < \frac{t(k+x)}{I-t} \quad \ldots \ldots \quad (6)$$

If this condition is maintained under all circumstances the earthing is, from the shock point of view, satisfactory, since it ensures "at all times an immediate discharge of electrical energy without danger." It necessarily follows from this that however well earthed B is, it is not safe if y is less than the value of the expression $t(k + x)/(I - t)$, in which we have two factors (x and y) which are readily obtained by test, one (I) which will, we hope, be known in each case, and two (t and k) which are unknown. The author is, however, of the opinion that a safe value for t may reasonably be assumed, and he suggests 20 mA.

The value of k varies enormously, but since we are assuming that it includes the resistance of the two contacts and as, in practice, even fair contact at both ends is extremely improbable, the assumption of a fairly high value is justifiable. It must also be remembered that the value for k will include the resistance of the fault itself which, in practice, will not be inconsiderable on account of the insulating properties of paint, rust, dust, dirt, etc. The author therefore suggests 5 000 ohms. In this connection it is interesting to note that, in the comments so far received, the value for t has generally been accepted and that for k has been severely handled. At the same time it has been suggested that the proposal would be simplified if, instead of limiting the current, the drop across K were limited to 100 volts. Ohm's law being what it is, this, the most frequent and certainly the most valuable comment, suggests a measure of reason in the

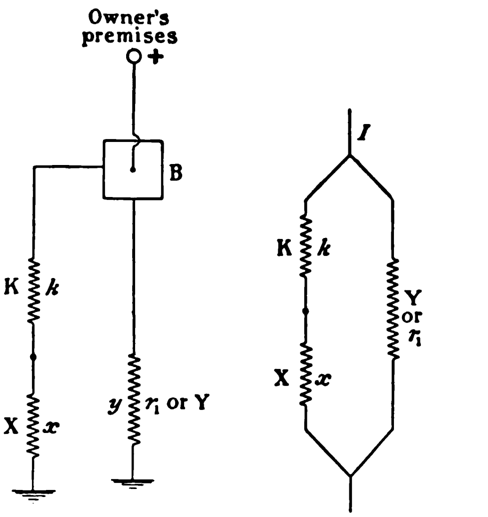

FIG. 2.

assumption of a value of 5 000 ohms as the resistance of the human body under poor conditions of contact.

The suggestion to limit the drop across K, i.e. between the earthed member and any point within touchable distance of it, is an improvement on existing procedure, but it necessitates assumptions no less uncertain than those of the values t and k. It will, presumably, be generally accepted that current is the principal factor in shock and that the fixing of a safe value for t offers little scope for controversy. If, therefore, the current is fixed, the permissible drop across the earthed member and any point within touchable distance of that member must vary directly with the resistance of the contact-making body; i.e. drop and resistance are equally variable.

Ignoring the contact resistance, can we definitely state upon what the variation depends? Probably the major portion of the resistance of the human body is in the skin and, if this is established, it would not be unreasonable to assume that moisture is the chief factor in the variation. This is capable of test and as moisture *in* the skin depends very largely upon atmospheric conditions—temperature and humidity—a range of reliable safe values for k might be fixed to cover all practical applications. But this is merely *en passant*.

Our expression now becomes

$$y < \frac{0\cdot02(5\,000 + x)}{I - 0\cdot02}$$

or

$$y < \frac{5\,000 + x}{50I - 1}$$

and, for all practical purposes,

$$y < \frac{5\,000 + x}{50I} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Now let us consider the case of a d.c. motor the maximum fault current of which is 14 amperes (i.e. $I = 14$). Let us assume the resistance of the motor frame to earth to be 4 ohms—a figure generally accepted as satisfactory for such a machine. Substituting in (7) we get

$$4 < \frac{5\,000 + x}{700}$$

$$x > -\,2\,200$$

But x cannot be less than zero and hence this value indicates absolute safety; for even if in (7) we substitute $x = 0$ we get $y < 7\cdot14$ ohms. In this case, therefore, safety is assured even if the touching body makes perfect contact with earth.

Now let us take the case of a d.c. motor the maximum fault current of which is 250 amperes and the resistance of the frame to earth is 1 ohm. Substituting in (7) we get

$$1 < \frac{5\,000 + x}{12\,500}$$

or

$$x > 7\,500 \text{ ohms.}$$

A combination of a heavy earth on this motor and the proximity of a water pipe, or even moist earth, suggests tragic possibilities. (In the author's district, local authorities rarely permit the use of water pipes for earthing purposes.)

These examples will suffice to show that mere testing between earth and the earthing system is inadequate, and that tests should also be taken between earth and points within touchable distance of the earthed member. A visual inspection will usually indicate which points should be tested, and if one lead of the testing set is connected to a metal rod or a 28 lb. weight and the latter is poked about here and there, the test becomes very simple and, practically speaking, takes up no more time than the single earth test.

The problem may be elaborated by the introduction of additional circuits, but investigation will show that these do not affect the question at issue, viz. the limiting of current through the shock circuit, and that all such circuits may be considered to form part of one of the two branch circuits under consideration. And, as there is only one path through K, the conditions remain the same.

The conclusion arrived at as a result of consideration of the question from this aspect is that adequate shock protection is ensured only when

$$y < \frac{t(k + x)}{I - t}$$

And this, the author suggests, is one of the conditions to be satisfied in all cases of earthing of metal objects other than conductors. Hence an owner may eliminate shock risk by improving the insulation of bodies lying within touchable distance of the earthed members, and so reduce the necessity for elaborate and expensive earthing. It should be distinctly understood, however, that this is the shock aspect only, and that its application in practice is limited by considerations of fault localization and the importance of not insulating a fault beyond that point at which it has been pre-arranged that it should cause the opening of the circuit. (In a.c. distribution reactance will, of course, enter into the calculations.)

The function of an earthing system being to eliminate risk from shock and fire, satisfactory earthing may be considered to be a form of insurance to the owner—an aspect of the case deserving of consideration by the insurance companies. But whilst an owner should be prepared to pay a reasonable sum for a satisfactory earth, it is desirable that the cost of earthing generally should not be increased. Further, application of a definition should not add to the cost or to the complication of testing and should strictly avoid interruption of supply for the purpose of taking a test.

A matter of very great importance in the testing of earths is the selection of a test earth. Water pipes are usually considered to provide excellent test points, but the reverse is frequently the case. The author recently had occasion to test the earthing of an industrial motor and its control apparatus. The owner had protested against an order to improve the earthing. A test was taken across the earth and a convenient water pipe and the result was undoubtedly high. A second water pipe was found some 30 ft. away and a second test was taken, but with the same result, which was again obtained on testing between the two water pipes—both on the same service with less than a dozen yards between them. A nearby well was then put into commission as a test point. The result was:

To earthing system	low resistance
To water pipes	high resistance

Moral: Do not judge a water service by its visible components.

THE LIFE-TESTING OF SMALL THERMIONIC VALVES.

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[Communication from the Staff of the Research Laboratories of the General Electric Co., Wembley.]

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SUMMARY.

The paper discusses the basis of a life specification for thermionic valves, similar to those in force for electric lamps, and indicates the assistance which a life-test equipment and data afford in preparing such specifications. The general characteristics of thermionic valves are then described, in relation to the problems involved in designing such an installation. Solutions of these problems are then discussed more fully, and a large installation for testing the life of valves is described. Typical examples of the results obtained are given.

(1) INTRODUCTION.

This paper is a fulfilment of a forecast in a previous paper,* that methods adopted in the life-testing of valves would subsequently be described. The present object is, therefore, to describe in some detail the valve-life testing organization with which the authors are associated.†

Certain advantages which are given by a life-test organization, such as the ability to control the production quality and to acquire knowledge of valve behaviour after many hundreds of hours' running, will be clear and need not be emphasized. In the same way, the assistance which a life-test installation affords in the design of new valve types will hardly need elaboration, particularly as the electric lamp industry has received material assistance in the past from similar installations. But the problem of running life-tests on thermionic valves is more complicated than the equivalent problem for lamps, due partly to the low operating voltages, and partly to the greater number of electrodes which are an essential feature of their construction. But despite dissimilarities from the case of the electric lamp, there is much that has been accomplished in the life-testing of lamps which can, with advantage, be applied to the testing of valves.

The valve industry will probably play as extensive a part in the present civilization, and one probably as valuable, as that played by the lamp industry. The time has already come when progress in development should be regulated by wise standards of performance fixed after a careful consideration of accumulated experimental data. This function has been performed for the lamp industry by the British Engineering Standards Association. At present valve types are multiplied almost at random, conforming to no universal standards of performance or manufacture, and the result is that, in this country alone, a bewildering number of types exists. The net result is of problematically small technical advantage to the user, and entails a sacrifice of the efficiency of manufacture, and uniformity of product, obtainable by standardization. It would seem inevitable that a British Standard Specification for valves should be considered, in the not far distant future, corresponding to the lamp specifications. Such specification would be most valuable if based on data which have accumulated during the life-testing of valves under carefully controlled conditions. It is hoped, therefore, that the present paper may stimulate interest in the preparation of such a specification, and also indicate methods by which reliable data may be obtained.

It should be made clear that, at present, only receiving types of valve are regularly life-tested in comparatively large numbers by the plant described in this paper, and any future extensions to cover the life-testing of the larger transmitting types are not discussed here.

In addition to the testing of valves with special experimental filaments, the life-test equipment has been used for tests on valves with bright tungsten filaments, with dull-emitting thoriated filaments, and with what are commonly known as coated, or "oxide" coated, filaments. The examples and remarks on methods of test given in the paper refer, however, only to the two former classes, as the considerable variations in total emission common to all "coated" filaments during life necessitate some alterations in the methods of checking the valve performance.

(2) GENERAL CONSIDERATIONS AFFECTING LIFE-TESTING OF VALVES.

The quantities which are of sufficient importance in receiving valves to warrant measurement during life are :—

(*a*) The filament current at rated voltage.
(*b*) The degree of vacuum.
(*c*) The total emission * from the filament at rated filament voltage.
(*d*) The voltage amplification factor.
(*e*) The internal impedance, as it is generally termed. By this is meant the ratio $\delta E/\delta I$, where $E =$ the anode voltage referred to the negative end of the filament, and $I =$ the anode current under specified conditions.

These are the factors which determine the performance of the valve when in use. In general, the

* "Thermionic Valves with Dull-Emitting Filaments," *Journal I.E.E.*, 1924, vol. 62, p. 689.

† This installation is established at the Research Laboratories at Wembley for testing the product of the M.O. Valve Co. Our acknowledgements are due to the Directors of the M.O. Valve Co.

* Or some other measurement which is very sensitive to changes in the total emission (see page 970).

life will be satisfactory so long as (*a*), (*b*) and (*c*) remain close to their specified values, since, in this case, (*d*) and (*e*) rarely alter. It is clear that the investigation of life performance will be sound, only if such accuracy and constancy is maintained in the test conditions throughout life that failures under heading (*a*), (*b*) or (*c*) are due solely to conditions within the valves themselves.

(*a*) *Filament current.*—Measurements of filament current at rated voltage provide a check on two important factors :—

(i) The manufacturing accuracy of the filament dimensions (length and diameter).

(ii) The rate of evaporation, during the life-test, of the filament material. This applies mainly to bright tungsten filaments, and also to a smaller extent to oxide-coated filaments.

With regard to (i), it is pointed out, later on, that it is advisable to obtain a more reliable check on the accuracy of manufacture by carrying out "rating tests" on much larger batches of valves, which are returned to stock and not subjected to life-tests.

It should be borne in mind that the life of the valve filament is very seriously affected by a small change of filament voltage (and therefore temperature) during the life-test. In the case of valves of the bright-emitter class, early failure will follow upon an increase of filament voltage, by actual burn-out of the filament, consequent upon rapid evaporation of the metal.

With dull-emitter valves the emission may cease early, due to the more rapid evaporation of thorium at the higher temperature, if the filament voltage is above its maximum rated value.

Clearly, therefore, constancy of filament heating supply is a vital factor in the life performance of valves, and it is important that the life-test conditions should be maintained constant during the whole life of the valves, so that any change of filament emission or filament resistance which may occur shall not be due to the test conditions. Only in such circumstances can the test-results be taken as reliable and comparable one with another. From life-tests on vacuum-type incandescent lamps it is known that a law for bright tungsten filaments may be approximately stated in the following form :—

$$L = A\left(\frac{1}{V^{15 \cdot 5}}\right)$$

where L = filament life in hours ;
V = voltage across the filament ; and
A = a constant.

This may be taken as applying reasonably closely to the case of the bright-emitter valve filament, so much so as to give a result of the correct order.

Thus for a given filament at two different voltages V_1 and V_2

$$\frac{L_1}{L_2} = \left[\frac{V_2}{V_1}\right]^{15 \cdot 5}$$

From this approximate relationship it is seen that a 1 per cent change of voltage, in the region of the normal voltage, will produce, in bright tungsten filaments, a change in life performance of the order of 16 per cent.

The case of the dull-emitter valve is different from that of the bright emitter in that the former is not, except by accident, liable to failure through burn-out of its filament, but rather through decrease in its dull-emitting properties alone. A similar law to that for bright tungsten filaments applies to dull-emitter (thoriated) filaments, and although the exponent of V has not yet been quite so accurately determined, its value is of the same order as for tungsten. Small changes in voltage, therefore, affect valve life profoundly.

Of the other factors which are measured during the life of a valve, that falling under (*b*)—the degree of vacuum—is next in order of importance.

(*b*) *Degree of vacuum.*—The modern valve is manufactured with a residual gas pressure not exceeding 10^{-4} mm of mercury, and any increase in this pressure is liable to affect adversely the valve life, particularly of dull-emitter types.

Assuming that the exhaust has been satisfactory in manufacture, the final degree of vacuum will be generally reached, by the aid of the magnesium "getter," in conjunction with the well-known electrical clean-up effect, within the first 100 hours of life, and the pressure will generally remain thereafter of the order of 10^{-6} mm. The only cause which may increase this pressure is the liberation of occluded gas from the electrodes or from the bulb, and such an occurrence will be due to some faulty detail in the manufacturing procedure, or to an accidentally applied overload causing overheating of the electrodes. In receiving valves the permissible range of anode voltage is much wider than that of filament voltage, since the power dissipated at the anode is so small that even proportionately large variations in its value make little difference to the temperature of the anode or of the bulb.

While discussing the degree of vacuum from the point of view of life-test, it may be advantageous to amplify the data previously published by us on the subject.* In the earlier days of dull-emitter valve manufacture, a gas pressure not exceeding 10^{-5} mm was considered to be imperative if the duration of the thorium emission was to be satisfactory. But pressures as high as 10^{-2} mm were permissible, provided that the residual gas was solely hydrogen, though the more rigorous limit of 10^{-5} mm was retained because it could not be guaranteed that only hydrogen would be present. The use of magnesium as an aid to exhaust, and further manufacturing experience, have since modified that limit. The action of the magnesium is to clean up the gases which militate against thorium emission, and to leave behind chiefly hydrogen, which alone is harmless. Thus it may now be stated that, with magnesium "getter," an approximate upper limit of 10^{-4} mm is entirely satisfactory. The usual method of arriving at the approximate gas pressure is to measure the reverse grid current due to ionization. There is then an empirical relation of the form

$$\frac{i}{I} = Kp$$

* Loc. cit.

where i and I = grid and anode current respectively, p = gas pressure in mm of mercury, and K = a constant depending upon the nature of the residual gas, the anode and grid voltages, and the geometry of the electrodes.

For the D.E.R. type valve, with an anode potential of 50 volts and a grid potential of -2 volts, and with hydrogen as the main residual gas, $K = 2$ approximately. For a pressure of 10^{-4} mm, and taking $I = 0{\cdot}5$ mA, we may solve for i, obtaining the value $0{\cdot}1\ \mu$A. This is therefore the limit of reverse grid current permitted on this type of valve, and vacuum tests are carried out, on those lines, enabling rapid determinations to be made with sufficient accuracy.

(*c*) *Total electron emission.*—A brief consideration of the relations between filament temperature and (*a*) voltage on the one hand and (*b*) emission on the other, will serve to show that the value of the emission changes very rapidly with voltage. From Richardson's equation $i = AT^{\frac{1}{2}}e^{-b/T}$ it is apparent that the emission is practically a logarithmic function of the temperature; it is also known that for a long tungsten filament at about 2 200° K. the voltage is approximately proportional to T^3. One would expect, therefore, that with changing filament temperature the emission will change much more rapidly than the voltage. Measurements on actual valve filaments show that a 1 per cent increase in voltage increases the emission by about 10 per cent for bright tungsten and by about 6 per cent for dull-emitting thoriated tungsten.

This point is important mainly in the measurement of valve characteristics during life test. The instruments employed must be of high accuracy, and the operator accustomed to taking close readings, if results obtained from successive valves are to be reliably comparable. Instruments which only just fall inside the British Standard Specification for sub-standard instruments are hardly good enough. In measuring the total emission it is usual to connect the anode and grid in parallel, and to measure the combined current at rated filament voltage and with a suitable anode-grid potential. The potential employed may be about 50 volts in the case of most receiving-valve types.

(*d*) *The voltage amplification factor.*—This is a constant for any one valve within reasonably wide limits on either side of the normal operating region, as it is dependent upon the geometry of the electrodes. The following empirical equation, due to H. J. Van der Bijl,* gives very good results and illustrates well the factors upon which this characteristic mainly depends :—

$$m = Cprn^2 + 1$$

where m = voltage amplification factor,
p = distance between plate and grid,
r = radius of grid wires,
n = number of grid wires per unit length,
C = a constant having the value 80 for the parallel-plane type of electrodes.

The accuracy of manufacture, therefore, determines the constancy of this characteristic between various valves of a type, but care has to be exercised in measuring it. By definition $m = \delta E/\delta e$, where δE = that change of anode voltage which would be equivalent in its effect on the plate current to a change δe in grid voltage.

It is usual, in order to facilitate the testing of large numbers of valves, to arrive at this ratio by taking two other ratios and dividing, thus :—

$$m = \left[\frac{\delta I}{\delta e} \div \frac{\delta I}{\delta E}\right] = \frac{\delta E}{\delta e}$$

where δI is the change in anode current occasioned by changes δe and δE in the grid and anode voltages respectively. Unless great care is exercised in making the measurements, the experimental errors may become comparable with those due to variations in manufacture.

The alternative method of plotting anode and grid voltages for a constant anode current is no doubt more accurate, but requires considerably more time. The ratio $\delta I/\delta E$ has to be measured, in any case, in order to determine the anode resistance, so that only $\delta I/\delta e$ is required, which merely involves two readings.

(*e*) *Internal impedance.*—The final characteristic to be considered is that known as the internal "impedance" or "internal resistance" of the valve. It should be noted that, in general, the term "impedance" is not strictly accurate, since it should include the inter-electrode capacity reactance, and the term "anode resistance" is perhaps preferable. In ordinary test procedure this inter-electrode capacity is neglected. Denoting this characteristic by R it may be defined as the ratio $\delta E/\delta I$. In routine work it is convenient to record δI for a constant change δE. The value of R obtained is less subject to serious error than was the case in measuring the voltage amplification factor m, but it should be noted that R is a function not only of the geometry of the valve, but also of the emission, and care must be taken to see that the filament voltage, which determines the latter, is correct. This characteristic is, therefore, one which may be adversely affected during the valve's life by incorrect life-test conditions, mainly incorrect filament voltage, leading to an impaired emission.

Rating Tests.

It will be seen that the procedure of life-test amounts simply to a series of tests of the rated characteristics of the valves during their life. As in the case of lamps, the number of valves manufactured is so great compared with the number which can possibly be tested, that it is usual to take rating tests on comparatively large batches of valves selected at random from stock, in addition to the limited number subjected to life-test. These large batches are then returned to stock. This procedure has been carried out in the case of incandescent-lamp testing in the past, and is now extended to valve testing. It is very valuable in enabling a closer check to be kept upon the general conformance of the product with its advertised rating, even though it gives no information about subsequent adherence to that rating. It may be of general interest to give a more detailed account of these tests, together with actual examples of the sort of spread of characteristics which is obtained in large-scale manufacture. The

* H. J. Van der Bijl: "The Thermionic Vacuum Tube," 1st edn., ch. 7, pp. 231 and 232.

batches of valves are obtained by haphazard selection of boxes of 50 from the despatch department of the manufacturer. The marked boxes are then sent to the laboratory, where the rating tests are carried out, without any preliminary treatment. To take one type, as an example of the routine, the measurements carried out are as follows (the rated filament voltage being 5 to 6) :—

(*a*) Filament current is measured at $E_f = 5 \cdot 4$, where E_f is the filament voltage.
(*b*) Total emission (I_e) is measured at $E_f = 5 \cdot 4$, and $E = e = 50$ volts, where E is the anode voltage and e the grid voltage.
(*c*) The quality of vacuum is determined by measuring the reverse grid current (backlash) at $E_f = 5 \cdot 4$, $E = 120$, and $e = -2$.
(*d*) Grid current (i.e. electron current) is measured at $E_f = 5 \cdot 4$, $e = +5 \cdot 4$, and $E = 120$.
(*e*) $\delta I/\delta e$ is determined by measuring I at $E_f = 5 \cdot 4$, $E = 100$, and $e = -4$ and 0.
(*f*) $\delta I/\delta E$ is determined by measuring I at $E_f = 5 \cdot 4$, $e = -2$, and $E = 100$ and 120.
(*g*) m, the voltage amplification factor, is obtained by dividing (*e*) by (*f*).
(*h*) R_a, the anode resistance, is the reciprocal of (*f*).

Target diagrams of which Fig. 1 (*a*) and 1 (*b*) are examples for two types of valves are then obtained by plotting m against R. In Figs. 1 (*a*) and 1 (*b*) are outlined also the limits for $\pm$ 20 per cent variation in m and R_a. Other types of valves are treated in a similar way, some or all of the voltages being different, depending upon the purposes for which the valve is most generally used. The main principle in every case is to make the measurements in the usual operating regions of the characteristics.

With most dull-emitter types, upper and lower limits are given for the voltage rating of the filament, which is designed to give :—

(*a*) Sufficient emission for satisfactory operation at the lower limit.
(*b*) A reasonable life at the upper limit.

This tradition in design is, of course, based upon the behaviour of the lead accumulator during discharge. The net result is that, provided the appropriate number of lead cells is employed, it is almost impossible for the user to shorten the valve life seriously by over-running the filament. This 10 per cent voltage range is of course only possible at the sacrifice of a certain amount of overall efficiency, and it is possible that the range may suffer reduction in the future, for the sake of greater filament efficiency.

When carrying out the rating tests, it is our practice to do so at the lower limit of the filament voltage range. Even then, with large amplifier valves, the total electron emission from the filament may be so great that, in measuring it, there may be dissipated as heat in the grid and anode an amount of power which is much greater than these electrodes have to withstand in normal operation. Indeed, with many types of oxide-coated-cathode valves it is useless to attempt a measurement of large amounts of total emission, because over-heating of electrodes causes liberation of gas which, when ionized, adds to the space current, and, by bombardment, causes additional heating of the cathode coating, thereby destroying any value which the emission measurement might have.

Considerations such as these have so far prevented us from rating valve filaments according to their electron emission, which quantity is, of course, strictly analogous in filament design to the candle-power rating of lamp filaments.

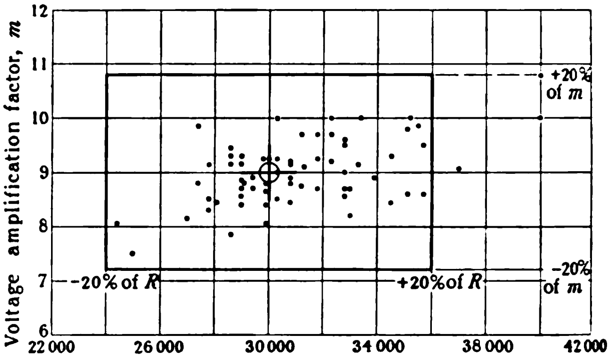

FIG. 1 (*a*).

In selecting lamps for life-test it is the practice to subject a large number to a candle-power rating test, and, from this large number, to select for life-test a comparatively small number, the candle-power ratings of which lie within the narrow central zone of the total spread shown by the large number. The average life of this small number which is life-tested, is, of course, much more truly representative of the average life of the factory product than would be the average life of a similar number of lamps selected at random, without the aid of a rating test.

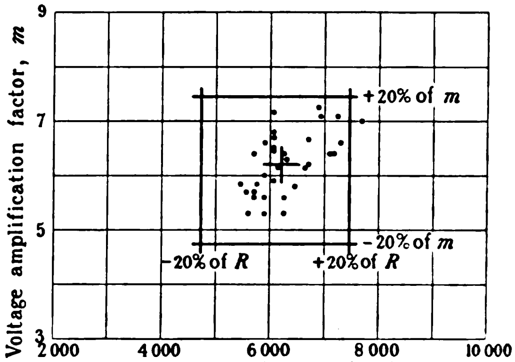

FIG. 1 (*b*).

Whenever the time comes to draw up a Standard Specification for valve life, the question of the method of selection of a batch for test will no doubt be of considerable importance, and it is unfortunate that the method of choosing for test a few valves, the filaments of which are operated at a temperature which is a mean for a larger number of filaments, is not directly applicable.

There is, of course, the oscillograph method of measur-

ing total emission, but this would probably prove to be too elaborate for incorporation in any proposed specification. Another possible method of fixing a total emission rating might be made dependent on emission measurements at a filament voltage considerably lower than the rated value; but the method would require an accurate knowledge of the voltage/emission relationship for all types of cathode, and might, therefore, be cumbersome and difficult to establish. In specifying the method of selection of valves for life-test there appears, then, to be no likely alternative to the choice of the completely haphazard method.

To return to the rating specifications themselves, altogether apart from life-test problems, there is with

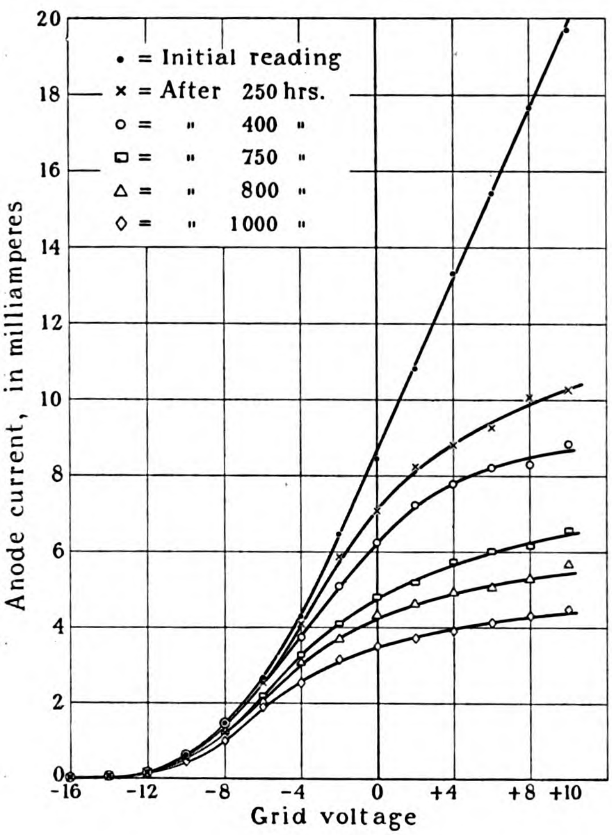

FIG. 1 (c).

them no real necessity to specify values of total emission. Total-emission measurements in receiving valves are, after all, principally made in order to ensure that there is amply sufficient to satisfy the anode characteristic, or; in other words, to ensure that this characteristic does not begin to bend over in the operating region. An alternative method of ensuring this would be to specify, for example, that

$$\left[\frac{\delta I}{\delta e}\right]_{e=+4}^{e=0} \not< \left[\frac{\delta I}{\delta e}\right]_{e=0}^{e=-4}$$

with rated filament voltage, and at the upper anode voltage rating. For purposes of illustration, an example of what happens to the anode characteristic as a result of rapidly decreasing emission is given in Fig. 1 (*c*).

SUGGESTIONS FOR A STANDARD LIFE SPECIFICATION.

The chief causes which terminate the life of a valve are :—

(*a*) filament failure,
(*b*) electrodes (or leads thereto) making contact with each other,
(*c*) loss of vacuum,
(*d*) loss of emission, with resulting deterioration in characteristics.

(*a*), (*b*) and (*c*) are all either self-determined or easily defined, so that (*d*) is the only factor for which it would be at all difficult to specify standards of life performance. In view of the difficulties in emission measurement, already discussed, a specification of emission life would probably be much more satisfactorily based upon measurements of anode characteristic. There are many possible modifications of this measurement which could be made at intervals during the life-test, such as :—

(*a*) the plotting of a short section of the complete curve,
(*b*) an internal resistance [$\delta E/\delta I$] measurement,
(*c*) some single point, which is very sensitive to emission change, such as the anode current (I_0) at the maximum rated anode voltage, with zero or slightly positive grid voltage, and rated filament voltage.

The life specification could then include a certain maximum permissible decrease (20 per cent or so) in I_0, or an increase in R_a of the same order, analogous to the permissible decrease in candle-power embodied in lamp specifications.

Some such specification of stability for I_0 or R_a would, if fulfilled, quite well ensure stability of emission, and, after all, the user of a receiving valve, whilst not directly interested in the stability of I_e, is keenly concerned with the stability of R_a.

(3) CONSIDERATIONS INVOLVED IN THE DESIGN OF A LIFE-TESTING INSTALLATION.

These points will be discussed under the following heads :—

(*a*) The types of supply for filament, grid and anode, and their permissible degree of fluctuation and methods of regulation.
(*b*) Details of the installation at Wembley.
(*c*) The accommodation required in order that representative numbers of valves of all types manufactured may be tested.
(*d*) The installation for measuring valve characteristics.
(*e*) The system of filing and plotting the results so that the maximum information may be obtained from the tests.

(*a*) TYPES OF SUPPLY.

Filament-heating supply.—The principal difficulty in designing a valve life-test installation lies in arranging a suitable supply for the filaments. It is always difficult to obtain voltages constant to 1 per cent, having regard to such changes of load as occur due to the

failure of a filament in one valve of a batch, or to switching in or out of valves. The difficulty is enhanced with the wide range of voltages which must be provided.

A simple calculation shows that it is quite impracticable to adjust the voltages of a batch by feeding from busbars through a common rheostat. Thus, the number of valves all burning at, say, 6 volts off a 12-volt supply through a common rheostat must exceed 200 if failure of two of them, which may occur when the installation is unattended, is not to alter the voltage on the remainder by 1 per cent, whilst removal of valves for test would necessitate constant adjustment of the voltage.

One obvious solution which presents itself is to use a separate rheostat for each valve, coupled with a supply transformer (if such be installed) of large capacity. For a small installation of 100 or so valves this method might be adopted. It suffers, however, from serious drawbacks:—

(*a*) Provision must be made for testing the voltage on each valve separately. Apart from the necessary switching gear, sockets, or tapping switches, this involves unnecessary labour when a number of valves are being tested on the same voltage, as is often the case.

(*b*) Trouble is likely to arise due to varying contact resistances on the rheostats, and to voltage-drop due to current taken by the low-reading a.c. voltmeter.

(*c*) Rheostats of sufficient range and current capacity take a good deal of space.

Nevertheless, for a small installation, particularly if allowance must be made for many different voltages, this solution is probably the best. It can be used with either a d.c. or a.c. supply, the latter having the great advantage that step-down transformers can be used with tappings to give low voltages, so that the whole installation can be fed from the customary high voltages. Whatever supply is used, however, it is clear that special steps must be taken to maintain it constant to within 1 per cent, a constancy which is, of course, not attained with any ordinary commercial supply.

The alternative method, which has been adopted with satisfactory results in the installation to be described, is the supply of small batches of valves from 415-volt busbars, kept constant within $\pm \frac{1}{2}$ per cent by an automatic voltage regulator, through induction regulators and step-down transformers. Such an installation is capable of expansion to cover many hundreds of valves, and requires no attention beyond the daily routine check of voltage on each batch of valves. With a suitably designed transformer and induction regulator the effect of failure of some of the valves is negligible.

The induction regulators, being on the supply side, may be of standard type. The number of valves to be fed by one transformer, and the number of transformers controlled by one regulator, depend on the size of batches and degree of flexibility required. Details of a particular installation are given below.

In deciding on such an installation, it was, of course, necessary to be satisfied that the results obtained by testing with alternating current would give the desired information, having in mind the fact that valves are normally burnt on direct current. That this is very probably so has been shown by a large number of tests carried out on batches of similar valves by both methods. We also have evidence from the life-testing of lamps, where it has been shown that no essential difference exists. Care should be taken, however, in the case of valves normally requiring a very large emission current compared with their filament current, such as some types of transmitting valve. In such a case, however, the whole method of test would be different and the installation described is not intended to deal with them. In any case, it is to be remembered that what is chiefly required is a comparison between different types of valve, or between different batches of the same type, rather than an absolute figure to a high degree of accuracy.

Although, as has been stated above, our object in conducting life-tests has so far been directed towards obtaining reliable figures for comparison, rather than data directly applicable to the conditions under which the valves are used by the public, it must be admitted that such data may one day be required. We do not anticipate that any great difference will be found between valve life on a.c. filament-heating, as against life on d.c. heating, but we cannot make a definite statement until further special and extensive d.c. tests have been run. General information, such as is forthcoming from large users of valves burnt on direct current, points to the correctness of our opinion, and it should be added that the practice of burning all valves on life-test at the upper limit of their filament voltage-rating will be undoubtedly more severe on them than are the d.c. operating voltages generally used.

The greatest differences between d.c. and a.c. testing will, of course, be obtained in valves in which the mean anode current bears the greatest ratio to the filament current. A very approximate estimate for a valve the thoriated filament of which requires a current of 120 mA at 6 volts, and which in normal use gives a mean anode current of 5 mA, indicates that under d.c. conditions, as a result of progressive loss of emission at the hotter negative end, the useful length of filament will be about 90 per cent of its initial value after completing 70 per cent of the life which is obtained when similar valves are tested at the same filament voltage, but with alternating current. In order to ensure, with this particular type of valve, that during d.c. operation no part of the filament shall be hotter than the hottest central portion would be under the 6 volts (a.c.) conditions, then the d.c. voltage would require to be as low as about 5·8 volts.

These figures deliberately overestimate the magnitude of the effect, for they neglect the appreciable amount of anode current emitted by the end of the filament which is within reach of the cooling action of the supporting wire, and they are also based upon conservative figures for the relation between life and temperature.

Anode and grid supplies.—These are still to be considered. In the case of the former, the use of direct current is desirable if the normal operation of the valve is to be imitated, and, since, unlike the filament voltage, there is no very close limit within which the anode voltage must remain, it is both con-

venient and satisfactory to obtain the anode voltage from a potential-divider. It is also satisfactory in practice to employ only one potential-divider, provided with four sliders, for four sections of valves.

The provision of the anode current from a separate d.c. generator, suitably driven and equipped, is preferable to the use of storage batteries, on account of the size of accumulator which would be entailed.

Finally, there remains the question of supply to the grids of valves under test. It is clearly important, if practical conditions are to be imitated, that valves of the low-frequency amplifier type should be life-tested with a definite grid bias. This involves the use of direct current, but the problem differs in several particulars from that of the anode supply. In the first place, the question is purely one of applying a potential to the grids, the current being inappreciable. The highest value of potential required is comparatively low and, in the case of smaller valves, not more than 1 or 2 volts. A supply is needed, therefore, which will remain constant in potential over long periods of time, and which is not required to provide power. It would clearly be uneconomical to employ rotating machinery for the production of such a supply. The use of dry cells is unsatisfactory on account of deterioration, whilst the lead-plate accumulator battery is not suitable where long periods of inaction are necessary, as in this case. A satisfactory supply is to be found in the use of nickel-iron storage cells, which offer the following advantages :—

(a) High permissible charging rate.
(b) Low voltage per cell (1·25 volts normal), thus allowing suitable voltages to be obtained without the use of potential-dividers.
(c) Low self-discharge.

These cells can be allowed to stand for much longer periods when in a charged condition, without recharge, than can the lead accumulator, and, moreover, a slow trickling discharge does not appear to cause deterioration to the same extent as in the more usual type of battery.

Thus, provision for the grid supply is satisfactorily made by a battery of these small nickel-iron cells, and this may feed the entire installation, each section of valves having a selector switch by which any one of a series of predetermined voltages may be tapped from the battery.

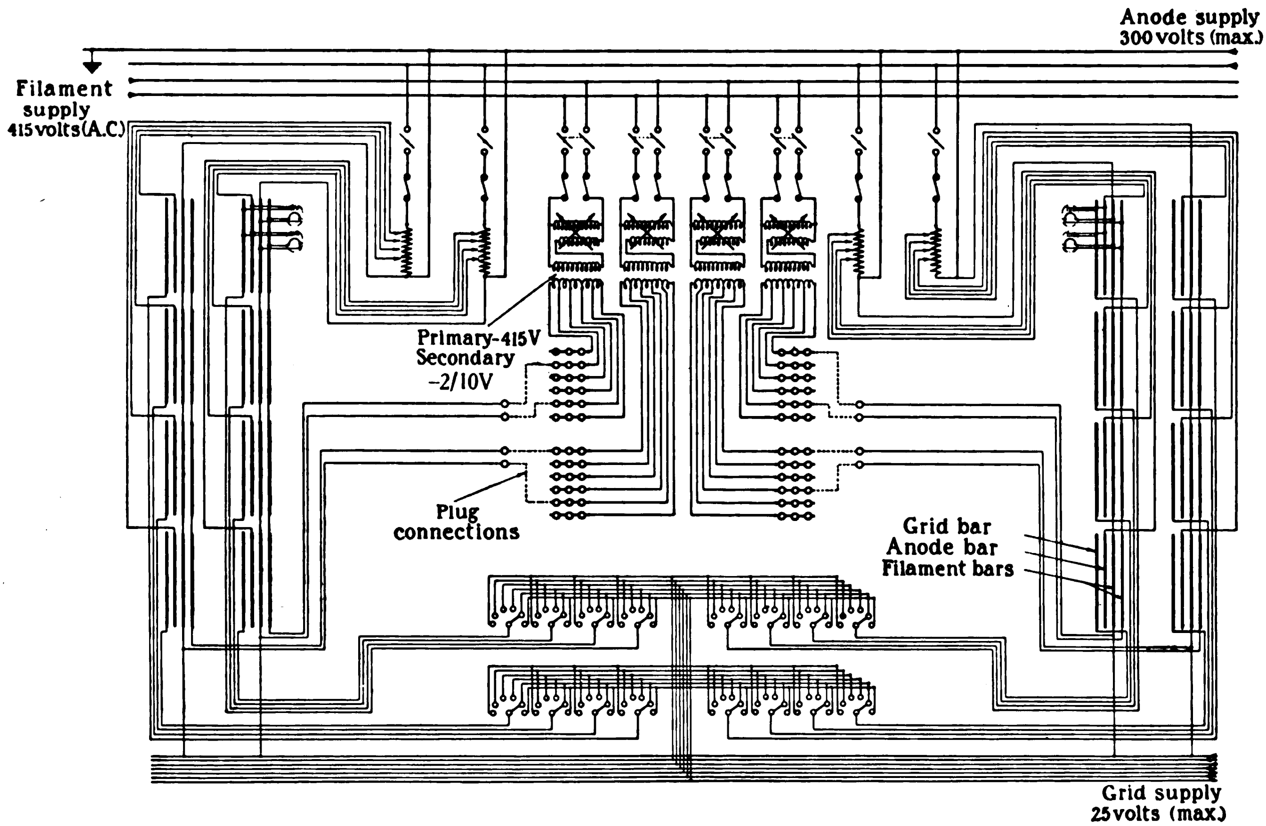

Fig. 2.

(b) Details of the Installation at Wembley.

For filament and anode-current supply a special motor-generator set is installed. This set, which was designed for lamp life-test work, consists of a 90-h.p. 415-volt three-phase motor directly coupled to a 50-kW 415-volt single-phase alternator, and, on the same shaft, two 2·5 kW 150-volt d.c. generators, the latter electrically connected to provide a 150–0–150-volt three-wire supply.

Fig. 2 shows a complete diagram of connections, and Fig. 3 the actual arrangement.

The 415-volt alternator is regulated by means of an automatic voltage regulator, which maintains the voltage constant to within $\pm \frac{1}{2}$ per cent. The valve anodes are fed from the 150–0–150 d.c. system. The framework holding the racks and local control-gear is of angle iron, mounted parallel to, and about 3 ft. from, the wall, the racks themselves being fixed to, and projecting from, this framework, thus forming alcoves, each of which is about 3 ft. wide. The control panels for each alcove are supported on the angle iron between the racks, and the transformers and other heavy gear are installed behind the panels.

Since all the racks are similar, it is only necessary to describe one alcove (a typical view of which is shown in Fig. 3). The whole of an alcove, with its attendant gear, only occupies a floor-space of approximately 4 ft. × 3 ft. Each consists of half of two projecting racks, the control panels being between them, and the heavy gear mounted behind.

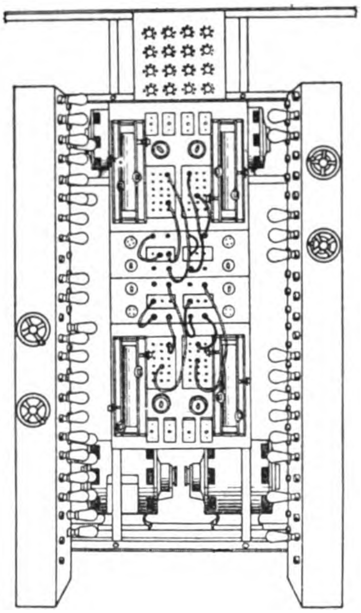

FIG. 3.

Each alcove has a capacity of 96 valves, arranged in four vertical sections of 24, two sections being mounted on each side of the alcove. Separate filament control is arranged for each section, which, in addition, is divided into four sets of six valves with separate anode and grid control. In other words, each alcove of 96 valves has accommodation for 16 sets of six valves with variable grid and anode voltages, these sets being arranged in groups of four, each bank of 24 valves so formed having separate filament-voltage adjustment. A reference to the diagram of connections will make this arrangement clear.

The control panels are of slate, and have mounted upon them the circuit switches and fuses for the filament and anode feeds, the anode potential-dividers, the filament supply socket bars, and the filament rack sockets. The actual valve-holder racks are of wood, with bakelite fronts, on the face of which are mounted the valve-holders, the supply busbars being carried at the back. To ensure good contact between the valve pins and the sockets, the latter are made self-aligning, so that any slight difference in the centres of the pins is taken up by the sockets.

For the filaments, the 415-volt supply is brought to the primaries of $\frac{1}{2}$-kVA transformers, having tappings on the secondaries at 2, 3, 4, 7 and 10 volts. In the primary circuit of each transformer is connected an induction regulator, capable of boosting and bucking $33\frac{1}{3}$ per cent of the normal voltage, and the transformer secondary tappings are so arranged that this variation on the transformer primary will give a continuous range of voltage from 1·33 up to 13·5 volts on the secondary.

Each secondary tapping is taken to a socket bar mounted on the control panels, and further sockets are connected to the filament bars of the racks. There are thus no moving contacts in circuit with the filaments—a very important feature. When setting up valves, a plug connection is made by flexible leads between suitable socket bars and the filament sockets. The plug-and-socket joints are well-made tapers, and excellent electrical contact is ensured, provided that care is taken initially in fitting the tapers.

Too much stress cannot be laid upon this question of contact voltage-drop. In the system described here, any contact may be called upon to carry a normal full load of 50 amperes, and for this reason it is the best practice, in view of the low voltage, and the close regulation required, to solder cables to the transformer secondaries rather than to make bolted connections thereto. Extra-heavy cables should be employed, and, in the design of the transformers, the copper should be increased so that the iron losses predominate, in order that the voltage regulation may be improved.

The question of flexibility is very important. We have found that subdivision of the filament supplies, so that each batch of 24 valves is independent as regards filament voltage, is barely sufficient. The designer should aim at subdivision into independent batches of 12 valves, and should also arrange that a portion, at least, of each 12 is so equipped that a series rheostat could, in special cases, be readily introduced into each filament circuit. Such a system would allow the testing of small batches of valves at unusual voltages, without disorganizing the routine work or causing numerous other sockets on the same voltage to stand idle, and the auxiliary system of single rheostats would not give rise to regulation trouble in the event of valves burning out.

Returning to the description of the plant, the anode supply is solidly connected through a potential-divider of 1 400 ohms resistance to the anode bars.

For grid supply there is mounted above each alcove a panel containing 16 small 6-point selector switches, one switch for each set of 6 valves. The switch points are connected to tappings on the grid battery, the range covering 25 volts, and the switch arms are taken direct to the grid bars.

(c) AMOUNT AND NATURE OF ACCOMMODATION REQUIRED.

The amount of accommodation, in the case of the plant under discussion, has been based upon figures

which have become recognized as standard in the life-testing of incandescent lamps. A compromise has to be effected between the testing of large numbers and the cost of such testing—both the initial cost of plant and the running costs. As with types of lamps in which the production is very large, running in some cases to hundreds of thousands per week, so with valves does the number tested have to be a very small percentage of the total production. In our case, the number of valves tested per week is of the order of 1 per 1 000 produced. Now it must be remembered that if, for example, 1 valve per week is taken, accommodation has to be provided for 6 such valves, since, on the basis of 1 000 hours' life-test, approximately 6 weeks are required to complete the test on each valve. Testing provision has therefore to be made for 6 times the number of valves collected from production per week.

installation under review, provision is made for experimental and modified valves equal to that for stock production valves, for the research work necessary in producing a successful new type of valve will involve the testing of many trial valves over periods of months.

These are the chief considerations which influence the accommodation required in a plant adequate for its purposes. In the installation discussed in this paper, a satisfactory compromise has been made by providing for approximately 600 valves to be burning at one time.

(*d*) The Installation for Measuring Valve Characteristics.

To deal with the characteristic testing of 600 life-test valves, at least two permanently equipped test-tables are needed. Direct current, with series-resistance

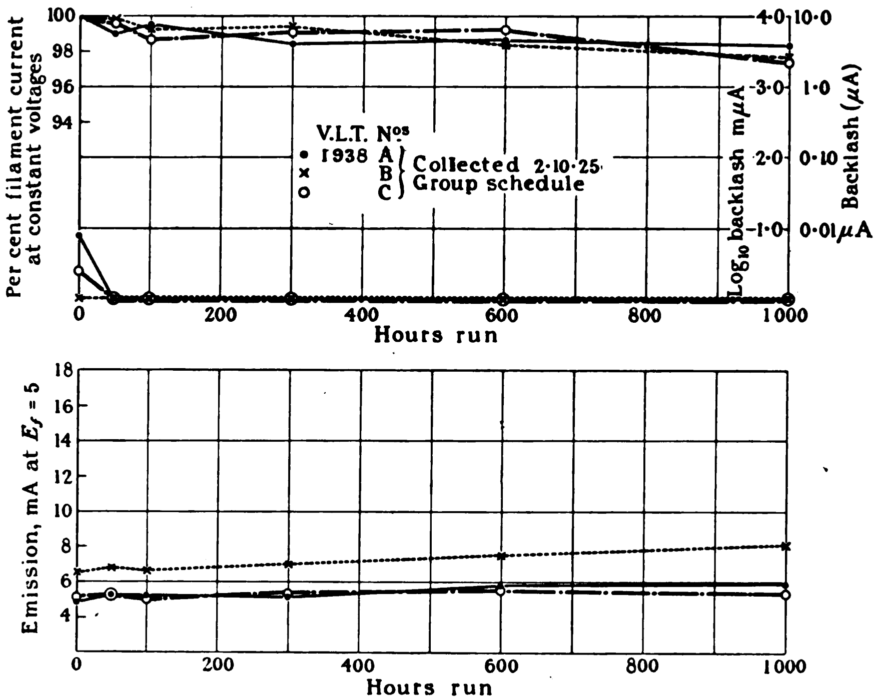

Fig. 4.

In the case of valves which are made only in comparatively small numbers, such as special types for short-wave work, or the larger types of power valves, the number tested will naturally have to be greater than 1 per 1 000 per week, as, in general, it is the best practice to collect valves for test at the shortest possible intervals, and certainly not less frequently than once per week. Where more than 1 valve per type per week is collected, the times of collection should be spaced evenly throughout the week. The significance of this factor is shown in the case of types produced in small numbers, for in such cases 1 valve per week should still be collected, and hence the collection figure may rise to 1 in 100 for certain types, or even higher, and every valve collected per week means that accommodation for 6 valves has to be provided. In the

control for the filament supply, and potential-divider control for anode and grid supplies, is satisfactory. High-grade multi-range instruments are required for measuring, and the calibration of filament voltmeters is necessary at frequent intervals. Reflecting galvanometers with variable shunts, and preferably sensitive to 1/1000th of a microampere, are necessary for rapid estimations of vacuum. The design of such tables should allow for the quick provision of abnormally large filament, anode, or grid voltages for special tests, or for insertion of extra resistance in any circuit. Provision should be made in the wiring to allow for testing of abnormal valve types (such, for example, as the 4-electrode type), by bringing leads out, in parallel with the usual valve-socket leads, to terminals situated, preferably, above the table-level. The latter device

enables uncapped valves to be tested with the same rapidity as capped valves. All meters should be well illuminated and mounted close together, preferably inclined at an angle to the vertical in order to facilitate quick reading without parallax errors.

(*e*) THE SYSTEM OF CURVE-PLOTTING AND FILING OF RESULTS.

As this Section may perhaps be of less general interest than other matter in the paper, it is relegated to an Appendix, where full details are given.

(4) EXAMPLES OF THE OPERATION OF A LIFE-TESTING ORGANIZATION.

So far as the general results of life-tests are concerned, the behaviour of bright tungsten filament valves is closely comparable with that of tungsten so until the valves were taken off test after 1 000 hours' running. The lower curves indicate a general rise of emission, at constant filament voltage, during life, indicating that the filament temperature increases gradually at points where evaporation of the metal has occurred, raising the total value of emission from the filament.

Fig. 5 shows typical results from good dull-emitter valves of uniform construction, run at the top limit of their designed voltage. The plotting of filament current is of little value with dull-emitting types, since the low temperature at which they run produces no observable thinning of the filament. It will be again noted that the vacuum became practically "dead hard" early in life, due to the electrical clean-up effect. The test-results shown were taken with a filament voltage of 5·4, but the life-test was run at 6·0 volts,

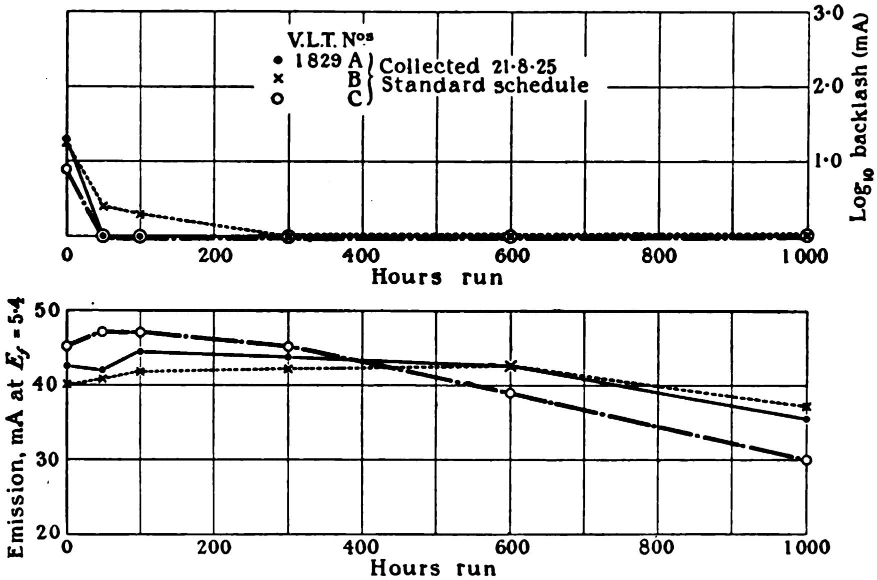

FIG. 5.

vacuum lamps, on which data have been published. Furthermore, the behaviour of the thoriated dull-emitter during life has already been discussed by Thompson and Bartlett.* In these circumstances a brief reference to the main life characteristics of both types will suffice.

Fig. 4 shows a typical set of curves upon a good batch of three bright tungsten-filament valves. Considering the top curves, it will be noted that the filament current at constant voltage decreases during 1 000 hours' life by about 3 per cent of its original value. This is due to evaporation of tungsten, at the high operating temperature, resulting in decreasing filament diameter and increasing resistance. Eventually the combined action of filament tension and local overheating due to this cause results in failure through fracture. (The bright emitter generally fails in that manner.) The middle curves show that the vacuum, though sufficiently good initially, was much better after 50 hours of life had expired, and that it remained

* Loc. cit.

which is the maximum rated voltage for the valve shown, and needlessly high for ordinary use. It is a good general principle in valve-life testing to run the actual test at the maximum rated filament voltage, and to take the characteristic measurements at, or about, the lower rated filament voltage. Valves which are satisfactory under such test conditions would be satisfactory to the user. It will be seen that there is a slight decline of emission during life, but all the valves still had, after 1 000 hours, 50 per cent more emission than would be required for satisfactory operation.

APPENDIX.

THE SYSTEM OF CURVE PLOTTING AND FILING OF RESULTS.

It is impossible to lay down hard-and-fast rules, but certain general principles may be indicated.

First, a system should be initiated whereby every valve of the 600 which may be burning should be capable of

rapid identification, and full particulars of its design data, etc., easily available. This involves a series of stock sheets such as that of which the top is illustrated in Fig. 6, giving the position and number of any valve, and preferably a series of small cards such as are illustrated by Fig. 8, the cards being held in a clip provided at each valve socket. By this combination of cards and sheets, it is assured that the valve concerned shall fulfilling the functions just described, ensures also, if the small rack card is continuously left in its clip until the valve either completes its allotted life period or fails, that the socket belonging to that valve must be regarded as occupied, even if the valve is removed for purposes of measurement. Confusion is thus avoided when several operators are at work, and one may be wishing to place valves on life-test while another has

Drawing number	Type	Date for 1 000 hours	600	300	100	50	Commencing date	Life test number	Index number	Res. assistant	Experiment number	Filament volts	Grid volts	Anode volts	Number of valves	Rack number	Remarks
2043		6/1	20/12	8/12	30/11/25	28/11/25	26/11/25	2078		S		5	0	50	3	17C	13/11/25 Group Schedule

FIG. 6.

VALVE LIFE TEST No. 2078

______Valves. Filament Volts = 5 Grid Volts = 0 Anode Volts = 50

Remarks: 13/11/25 GROUP SCHEDULE

Date	Hours	Filament characteristic and rating		Vacuum		Grid, i	Valve characteristics. $E_f = 5$									
		$E_f = 5$ volts		$E = 150$ $e = 2$		$E = 50$	$E = 50$		$10^5 \times K_1$ mhos	$e = 0$		$10^5 \times K_2$ mhos	m	$10^{-3} \times R$ ohms		
		$\left.\begin{matrix}E\\e\end{matrix}\right\} = 0$	$\left.\begin{matrix}E\\e\end{matrix}\right\} = 50$	Total, i	Leak, i	$E_f = 5$ $e = 0$	$e = -1$	$e = +1$		$E = 40$	$E = 60$					
		I_f	I_e				I	I		I	I					
26 Nov.	A	0·720	5·92	−58	−1	6·9	1·01	1·57	28·0	0·95	1·52	2·85	9·83	35·1		
28 Nov.	50	0·716	8·41	−6	0											
30 Nov.	100	0·714	8·34	−3	−2											
18 Dec.	300	0·710	7·19	−1		7·8	0·95	1·49	27·0	0·91	1·58	3·35	8·06	29·9		
20 Dec.	600	0·70	8·01	−1												
28 Dec.	800	Filamen	t Failu	re												
26 Nov.	B	0·712	5·41	−112	−1	5·8	0·85	1·43	29·0	0·83	1·47	3·2	9·07	31·3		
28 Nov.	50	0·710	6·89	−10	0											
30 Nov.	100	0·702	7·67	−8	−2											
18 Dec.	300	0·702	7·21	−3	−3	5·8	0·82	1·39	28·5	0·79	1·48	3·45	8·27	29·0		
20 Dec.	600	0·70	7·60	−3	−3											
6 Jan.	1 000	0·670	7·91	0		6·1	0·75	1·26	25·5	0·73	1·29	2·8	9·12	35·7		

FIG. 7.

have its characteristic measurements taken at the correct periods during its life. To each batch of valves, of every type, a serial number is allotted, and, in that batch, the valves are able to be identified by carrying a distinctive letter. Thus, a batch of valves might, for example, have the serial number 2078, and a given valve of that batch might be 2078A. This classification numbering is etched on every valve, and is also marked on the small card (Fig. 8) clipped beside the valve during the whole of its life. This system, whilst entirely valves removed for the measurement of characteristics. This point is of greater practical importance than might appear at first sight.

Measurements are made upon the valves in general at 0, 50, 100, 300, 600 and 1 000 hours during life, though at more frequent intervals in certain cases. The results are recorded in such a way as—

(*a*) To illustrate, in a graphical manner, the behaviour of the valves and thus to enable the manufacturer to modify his methods of production where

necessary, with the minimum of delay. To accomplish this, cards are prepared for each batch of valves (see Fig. 7), so designed that complete information is given of all the ordinary characteristics. In addition, two blank columns on the right-hand side of these cards enable measurements on additional properties, such as

VALVE LIFE TEST. No. 2078A

Exp. No. ____________

Type or Name

____

E_f 5·0

E 50

e 0

Remarks: Stock

FIG. 8.

detector action and degree of microphonic property of each valve, to be recorded if desired. The more important results entered are then plotted on tracing paper (see Fig. 11), and blue prints of these graphs are sent to the manufacturing sections producing the valves.

(*b*) To amass data which may be analysed from time to time, so providing statistics covering the whole range of the production schedule over periods of months, enabling valuable deductions to be made as to the effect

____________ Factory. V.L.T. No. 2078

STOCK
VALVE LIFE TEST

Drg. No. V.L.T. 2043 F

5·0 Filt.
0 Grid } Volts
50·0 Anode

Res. Asst. }
Wks. Supt. } ____________

Date 26/11/25

Life Test of 3 Valves

Manufactured 13/11/25

on Life Test 26/11/25

Remarks: Group Schedule

FIG. 9.

INTERIM REPORT ON VALVE LIFE TEST No. 2078A

Date 28/12/25 Failed at 800 Hours

Remarks: Filament Failure.

____

Number of Valves Burning 2/3

Valve retained by ____________

FIG. 10.

of small changes in design, and so forth. In Fig. 9 is reproduced a slip which is made out in triplicate, one copy for works' information and two for reference, as

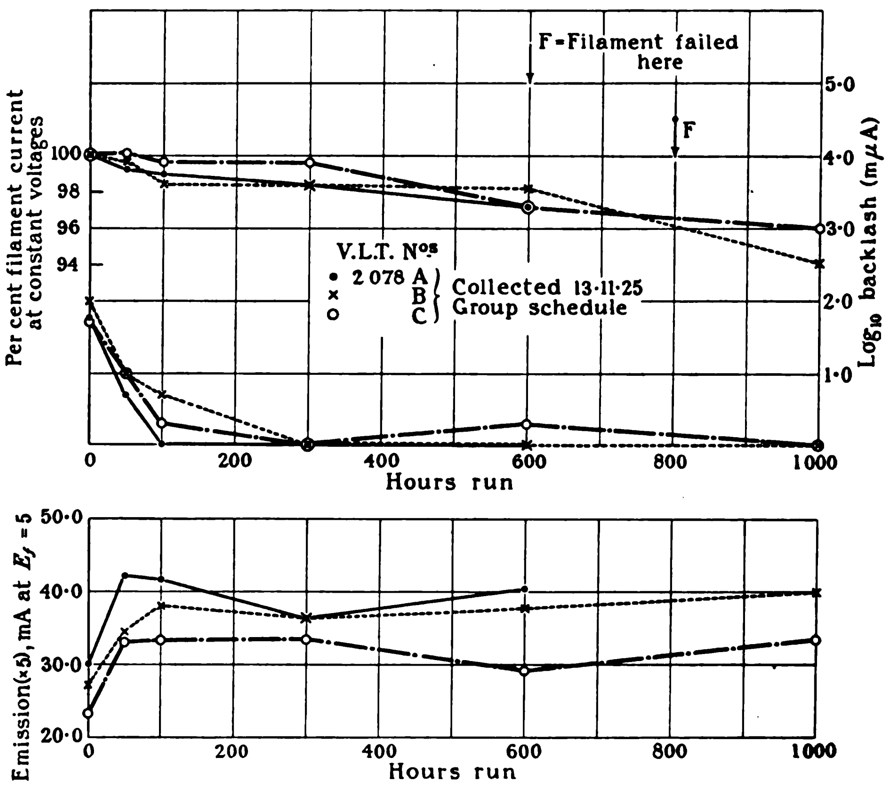

FIG. 11.

soon as a batch of valves is put on life test. An exactly similar procedure is adopted with the slip illustrated in Fig. 10, which is made out when any single valve of a batch fails on life-test.

To make the system in use at Wembley clear, the case of a batch of two valves of stock production will be considered, in which one valve is entirely satisfactory, and one fails after some hundreds of hours' running.

These valves, in common with all stock valves tested, are selected at random by a representative of the testing laboratory, and are chosen during the last stage of manufacture. On arrival at the Laboratories they are checked against the collection schedule for that type of valve, are then each given a distinctive number, which is etched on the bulb, and their full details entered in the valve file (Fig. 6). Their life-test card is then filled in (Fig. 7) with the test-condition figures and date, and the initial characteristic readings are taken upon them, after which they are placed on the life-test racks, their rack cards (Fig. 8) being clipped beside them. At the same time the works are advised by a slip (Fig. 9) that the test has begun. On the proper dates, as shown in the valve file, they are taken from the racks and their characteristics are again measured and entered on the life-test card. Let us suppose that valve 2078A fails. The works are advised on the slip shown in Fig. 10. During life the main results accumulating on the life-test are plotted on a transparent graph sheet (Fig. 11), and, at the conclusion of the life-test, blue prints of the graphs so recorded are despatched to the works. The life-test cards are filed at the Laboratories to contribute data subsequently to statistical records.

Communicated Remarks.

Mr. R. C. Clinker: The data given by the authors will prove serviceable when the time arrives for valves to be standardized. The advantage accruing to the manufacturer as a result of life-tests is indisputable, and the maintenance of a constant check on life is a necessity. As regards the design of life-testing equipment, I note that the authors have definitely adopted alternating current for filament heating, as they are mainly interested in comparative figures rather than in the life when run under normal working conditions on a d.c. filament supply. I am inclined to think, however, that they have rather overstated the difficulty of keeping a constant voltage on the filaments. For 6-volt valves it seems unnecessary to drop more than 2 volts in the common rheostat (instead of 6), and a filament failure then affects the voltage on the remainder to a much smaller extent. It is certainly desirable to avoid a multiplicity of rheostats with their possible varying contacts. The testing intervals given on page 977 seem to be somewhat long. Are these the only intervals recorded for ordinary cases? Regarding the emission measurement, although it is true that observations of R_a or I_a are wanted in practice, yet these suffer from the disadvantage that a valve or batch of valves which may change their emissions rapidly in the early stages will not show this change unless, or until, it affects the anode current at $E_g = 0$. This test, therefore, would give a poor indication as to how a valve is behaving early in its career, although giving a definite indication of the end of useful life. A brief description of one of the life-testing equipments installed in the B.T.H. Co.'s laboratory at Rugby may be of interest. All valves are run on a d.c. filament supply, as it is desired to reproduce as nearly as possible the conditions obtaining in practice. Current is obtained from accumulators which are duplicated so that one battery can be charged when the other is running. The filaments of the valves are connected in parallel in batches of 12, and in series with a common filament rheostat, the voltage of the battery being not more than 2 volts greater than the rated filament voltage. A large-capacity battery is used, and the discharge current is kept much below the normal, so that the voltage variation over considerable time-intervals is small. These small variations can be corrected and check measurements made at convenient and specified intervals. Using this method, it is possible to keep the filament voltages constant to within 1 per cent or less, except in the special case in which a filament fails by open-circuit. This is of rare occurrence in dull-emitters and, in any case, is caught within a few hours. Each batch of 12 valves is provided with separate anode resistances and can be connected by means of a plug board to a convenient tap on the anode battery, which is a potential battery of relatively large capacity. The grid bias for each batch of valves is obtained from large-capacity primary batteries connected to a suitable plug board, so that any desired voltage can be obtained. The racks for the 12 valves are laid out in such a manner that a filament rheostat can be inserted, if desired, in order to meet special conditions. The layout of one unit of this equipment, suitable for testing batches of valves with a filament rating of 6 volts, for example, consists of a central slate control panel with the necessary rheostats, instruments, switches, etc. Four racks, designed to carry 12 valves each, are mounted on each side of this control panel. The wiring to the valve racks and instruments is easily accessible for purposes of calibration and checking voltages actually on the valve pins. The latter, however, is usually only necessary on special tests where separate filament rheostats are used with each valve.

Mr. T. E. Goldup: The life-testing of thermionic valves is a subject of extreme importance to the valve manufacturer in so far as it is an indication of the quality of bulk production, and in order to obtain reliable and consistent data with regard to the life of valves, an organized scheme of life-testing, where the conditions under which life-testing is conducted are those of constant filament potential and reasonably constant anode potential, is absolutely essential. In the dull-emitting type of receiving valves, failure during life is almost invariably due to the falling-off in the total emission, therefore the observation of this particular

quantity during life-test is of outstanding interest and, provided it remains above a certain predetermined level, one can assume that the characteristics of the valve will remain reasonably constant. In Section (2) of the paper, and also in the latter part of Section (1), the authors refer to the varying emission in oxide-coated filaments during life-test, and the unreliability of total-emission readings. While this is no doubt true in the case of the old types of filaments which were heavily coated with lime or barium, where the coating of the filament is at a considerably lower temperature than the core, it is certainly not true of that type of coated filament made by methods evolved during recent years. The target diagram of Fig. A shows the results during life-tests of such filaments, and it will be clearly seen that the variations between one valve and another, of the filament voltage and current for a given total emission, is remarkably small. It will also be observed that the magnitude of the variation actually decreases as the life-test progresses. The difficulties mentioned by the authors in connection with the measurement of total emission of oxide-coated cathode valves do not appear to constitute a problem that warrants the taking of static characteristics during life instead of the simple observation of total emission. If the exhaust during manufacture is thoroughly complete (which would mean the effective freeing from gas of the grid as well as the anode), the slight heating of the grid occurring during the total emission measurement should have very little effect on the reading. In a valve, for example, where the total emission is, say, 30 mA at a given filament voltage, the maximum power the grid could possibly dissipate with 50 volts on the anode and grid in parallel would be 1·5 watts during the emission test. Experience indicates that a good deal more power than this is required to heat the grid to such an extent that liberation of gas occurs, provided, of course, that the grid has previously been thoroughly freed of gas. It is worthy of note, however, that under normal conditions of filament voltage it has been found possible to run the oxide-coated cathode valves under total-emission conditions for several hours without any appreciable variation in the total emission. It can therefore be said that for at least one type of oxide-coated cathode the total-emission test can be applied during life test without unduly harming the valve, and such readings can be relied upon for the purpose of determining the performance of the valve in practice. The variations in R and m in Fig. 1 (a and b) indicate that much closer limits could be worked to than $\pm$ 20 per cent. In modern valve manufacture the bulk production is surprisingly consistent, especially so far as the m value is concerned. Fig. B shows a target diagram of a batch of oxide-coated cathode valves; it will be seen that the maximum variation in m is $\pm$ 7·5 per cent of the mean, and in R it is approximately $\pm$ 14 per cent. The question of the selection of valves for life-test is one for the individual manufacturers to decide for themselves, and they will naturally so arrange the selection that an effective life-test check is made at frequent intervals on their products, it being taken for granted, of course, that the valves chosen for life-test conform to some predetermined schedule. The question of whether life-testing should be done under a.c. or d.c. filament conditions is one which is largely determined by the type of valve to be life-tested. In the life-testing department of the Mullard Radio Valve Co. we have preferred to life-test under d.c. conditions, and it would perhaps be convenient to give here some details with regard to the installation. The supply for the filament is obtained from two specially designed low-voltage generators connected to the shaft of an a.c. motor-alternator. The latter is run from a 200-volt 50-cycle single-phase supply (there being no three-phase supply available) and ample cooling of both motor and generator is arranged for so that no over-heating occurs under normal conditions of continuous load. The wiring of the installation is shown diagrammatically in Fig. C. Across each low-voltage

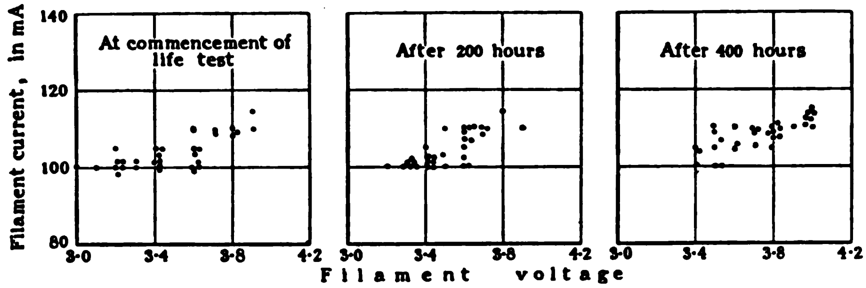

FIG. A.—Target diagrams showing filament current and voltage of P.M. valves for 20 mA total emission at various stages of life.

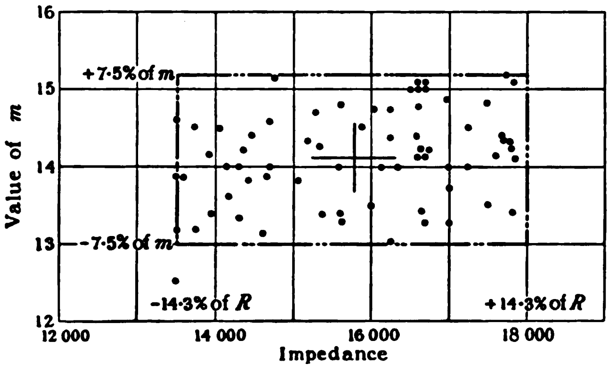

FIG. B.—Characteristic spread of P.M. 3 valves.

generator a low-resistance potentiometer is connected, thus enabling various potentials to be supplied by the one machine, and also ensuring a constant load on the generator irrespective of that due to the valves under test. The compounding of the generators is such that at full load and no load the terminal voltage remains practically constant, and, with the potentiometer constituting a permanent load on each generator, the insertion or removal of the valves makes no appreciable difference to the potential. Suitable voltmeters are permanently connected across the filament busbars. Fig. D indicates the general arrangement of a section

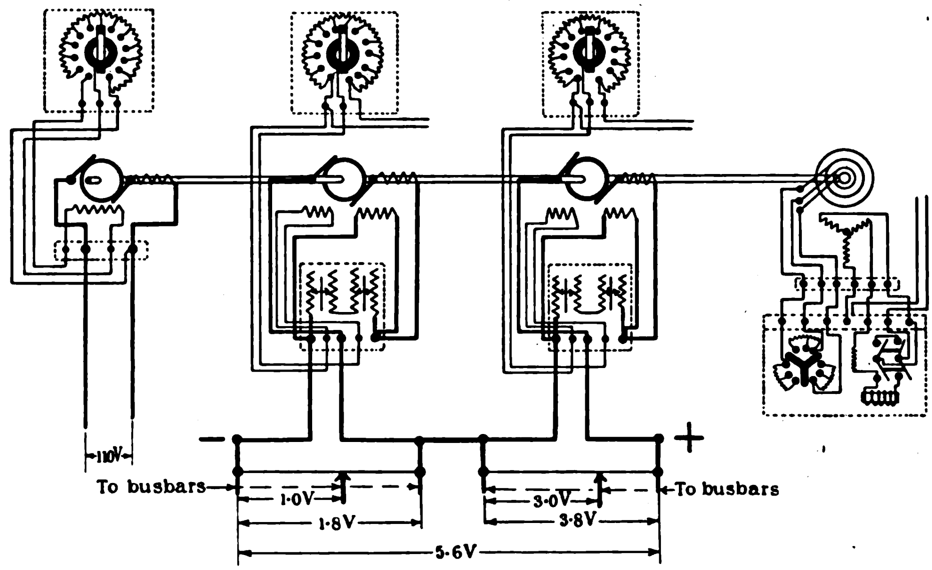

Fig. C.—Wiring diagram of life-test motor-generator.

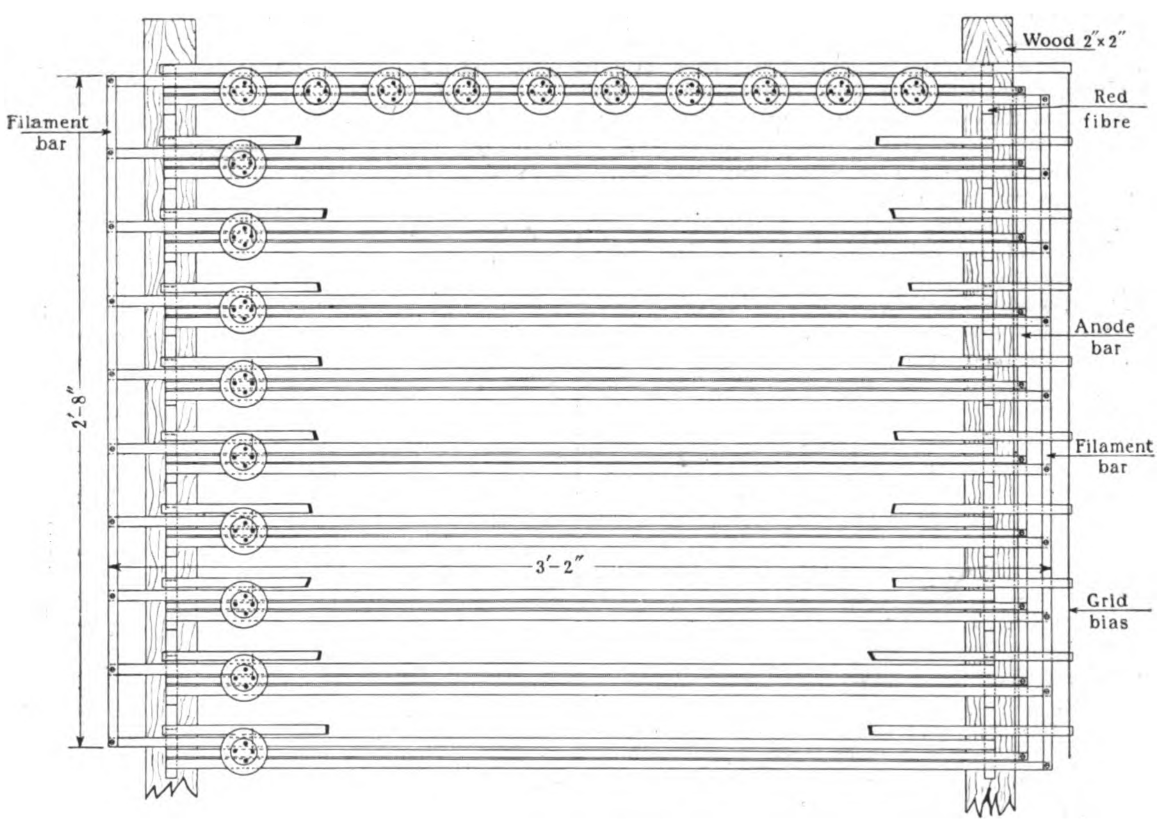

Fig. D.—Life-test screen.

of the installation which is capable of accommodating 100 valves. The anode and filament connections of the valve sockets are sweated to the horizontal busbars, and these in turn are connected to the potentiometers with copper strip $\frac{3}{8}$ in. wide and 0·1 in. thick. The anode potential for the installation is supplied by a d.c. machine which is connected to the same shaft as the low-voltage generators. A potential-divider is used for obtaining various anode voltages in different sections of the installation.

Mr. N. F. S. Hecht : For several years I have been engaged on life-testing valves, but as only one or two valves were tested at one time no problem of power supply has arisen. On the other hand the investigations with which I have been concerned have been directed mostly in the direction of forced life-tests on bright-emitter filaments in transmitting valves. In the case of low-power valves having a filament life of 50 hours or less no serious delay is caused by running the filament at its normal voltage, but in the case of larger valves having a filament life of 200 hours and above, considerable delay would occur in the acceptance of batches of valves delivered by the manufacturers if a normal burn-out had to be reached before the acceptance papers could be signed. Investigations were therefore carried out to determine the law connecting life and filament current or filament voltage and to ascertain the degree of reliability of such a law and its applicability to all sizes of bright-emitter filaments. In these investigations it was preferred to refer life to filament current instead of filament voltage as it was found that very appreciable variations occur between different makes and different types of valves owing to the voltage-drop in the connecting wires between the valve pins or lead-ends and the actual filament. This variability is avoided by taking measurements of filament current. The law connecting filament current and filament life was found to be $L = AI^{-18 \cdot 5}$, where L = life, A = constant depending on the dimensions of the filament, and I = filament current. For similar valves taken from different batches this law is subject to fluctuations in the index, the lowest value ever recorded being 17 and the highest 20·5. This variation, however, does not seem to have any connection with the dimensions of the filament and is very small for valves of the same batch. Knowledge of this law therefore made it possible to carry out life-tests at a filament current higher than normal, the current ratio being varied for different types of valves. This enabled life-tests to be completed in a day or two instead of weeks. I ought to state, however, that valves are not rejected on the result of this test; it is merely an expedient to expedite acceptance. Before this test can be accepted as standard and binding between manufacturer and user it would require confirmation and publication by some accepted authority such as the B.E.S.A. I have referred to this aspect of life-tests on account of the authors' statement at the foot of page 968. Here the law is given as $L = A\left(\frac{1}{V^{15 \cdot 5}}\right)$. It seems to me that the index is extraordinarily high; in my experience bright-emitters have never shown a higher value than 12 and it has been as low as 10, the average being about 10·7. I believe that Mr. Buckley, of the National Physical Laboratory, has obtained figures slightly higher than these but still considerably below the value given in the paper. It is interesting to hear that the law for dull-emitter filaments is similar to that for bright-emitters, and I hope the authors will be able to make a further statement on that point in due course. In conclusion I should like to state my appreciation of the authors' efforts to show the need for standardization of valves and valve testing. There is no doubt that the present multiplicity of types is no less confusing than the multiplicity of designation; I think it would be a great convenience if some definite and universal scheme were recommended by some such body as the B.E.S.A. and accepted by all manufacturers. Some of the existing methods employed to describe different types of valves are excellent but unfortunately they are employed by one or two manufacturers only.

Dr. B. Hodgson : Most people will agree that the principal factors to be measured are the filament current at a certain voltage, the vacuum and the total emission. Life-test factors depend upon the state or proficiency of the art of valve-making and it is assumed, in our opinion correctly, that failure due to lack of rigidity of valve parts or to poor quality of glass, etc., are only a small fraction of the total of finished valves, and attention is concentrated upon the most sensitive part of the valve, the filament. We have, however, two distinct uses for life-tests. The first is to discover the actual average life of a particular type of valve and ascertain how the individual valves of this particular type differ among themselves and deviate from the standard design. This test has for its object a check upon the factory acceptance tests of the valves, and yields information as to which particular branch of the manufacture needs improvement. The second use is to test the efficiency of different methods of manufacture or of different materials, apart from the variations of individual valves of a particular type. This is the test of one batch of valves against another, whilst the first use is a test of an individual valve against another of the same type. Now the filament suffers injury from three causes:—(1) Evaporation, (2) disintegration due to bombardment, and (3) physical or molecular changes. All these act together and it is difficult to distinguish or apportion the damage among these three. The filament current and voltage and total-emission tests are a check upon the filament dimensions; the disintegration is maintained below a certain amount by fixing a minimum backlash test; but no test exists for detecting changes in the constitution of the filament itself. (It might be mentioned here that most valve filaments are under *some* tension to prevent sagging and so making contact with the grid. The filament spring must be very carefully adjusted so as to put no undue tension upon the filament.) All these factors are influenced greatly by the temperature of the filament, and the loss due to evaporation, disintegration, etc., was greatly reduced by the introduction in receiving valves of the thoriated tungsten filament instead of the pure tungsten filament. Oxide-coated filaments have a further advantage over thoriated tungsten filaments in that the temperature is lower and the life consequently longer. Another

important result has been to observe that oxide-coated tungsten filaments suffer no appreciable deterioration in ductility: after a 1 000-hour run they can be bent and knotted without the slightest danger of fracture. There might be some difference in opinion as to the method of selection of valves for life-test. Valves may be selected haphazard from stock, but this might lead to erroneous conclusions because it is obviously impossible to life-test more than a very small fraction of the product. If target diagrams are used to sort out suitable valves it appears to us desirable to form the diagram with one of the variables, either filament current or filament voltage, or perhaps total emission. Both the quantities m and R_a used in the paper are dependent chiefly upon the geometry of the valve and, further, are not independent of each other. In general one can say that a high value of m and a high value of R_a will fall together and it would be expected that the points would lie along a slanting line. This is so in both the diagrams illustrated, and those valves represented by the centre of the target are those which have the expected and average geometry, and they may or may not represent the average life of the stock, according to whether the filaments in this batch are average or not.

Mr. H. G. Hughes: I should like to ask if the statement in Section 2 (*a*) concerning the application of the formula for lamp filaments to bright valve filaments has been tested and confirmed by the authors. Few of us have the opportunity of making a thorough investigation into such a problem, because naturally a very large number of valves must be consumed in the work and a very efficient equipment such as is described in the paper is essential; but the information would be most valuable to those concerned with valve design. It would be useful to know the range of voltage over which the formula holds good, and how it is affected, if at all, by the size of the bulb and the presence or absence of "getter."

Mr. L. C. Pocock: Although the authors have not dealt with valves having oxide-coated filaments, the growing popularity of this class of valve may justify the following remarks. The "considerable variation of total emission common to all coated filaments" referred to by the authors can be traced to two distinct causes: (*a*) Evolution of gas from electrodes during the first few hours of running; these changes may be very violent but can be prevented by proper exhausting. (*b*) Slow physical changes and evaporation of coating during life; these changes can be controlled by proper preparation of the filament, and they are then important only at the end of the filament life. The difficulty of making total emission measurements may be avoided in routine testing by measuring instead the increase of plate impedance for a given small decrease of filament current. When the total emissions must be accurately known the Davisson power emission chart may be used.* The authors do not mention a.c. bridge methods for valve testing. Bridge methods for measuring amplification factor, impedance and mutual conductance are well known, and experience shows them to be accurate and convenient.

* H. J. Van der Bijl: "The Thermionic Vacuum Tube," 1st edn., p. 82.

Colonel T. F. Purves: The methods described by the authors of dealing with the life-testing of valves on a large scale appear to be very similar in essentials to those at present carried out in the Post Office, except that alternating current is adopted for filament heating. In the Post Office tests the valves are run continuously under practically their working conditions; the correct anode potential is used and the grid is primed to its normal operating value. On page 970, in the routine measurements detailed in (*e*) and (*f*), it is noticed that the reading for (*e*) is taken with an anode potential of 100 volts, whereas the ratio $\delta I/\delta E$ in (*f*) is taken at 100 and 120 volts. Would it not be preferable to take this reading at 90 and 110 volts, as it is from these readings (*e*) and (*f*) that the amplification factor m is derived? It is noticed that the life-test curves given by the authors all stop at 1 000 hours. Presumably this is not the full life of the valves, and it would be interesting to know what life has been obtained from various types of filaments and valves. Can it be said what effect the continual switching on and off of the filament will have on the life of a valve? Have the authors considered the "slopemeter" test for obtaining the valve constants? In certain valves tested by the Post Office, the most marked change with length of service is not observed in their performance with normal voltage on the filament but in the more marked decrease in the amplification due to a given fall in voltage across the filament, as compared with that observed at the commencement of their life. This characteristic is of importance in practice, where periodical variations in battery voltages occur. Are tests of this characteristic made in the course of life-tests?

Dr. E. H. Rayner: The information given in the paper is of great value to anyone who has to do with the life-testing of valves. The descriptions both of the general arrangements and power equipment and also of typical results will be most helpful. I think it may be found that the relation between life and voltage as determined from experience with tungsten vacuum lamps may need some modification when applied to a valve filament a couple of centimetres long or even shorter. The effect of end-cooling may produce some modification, causing a temperature distribution different from that of the comparatively long filament of the vacuum lamp. Further information on this point, which is one of some importance as regards the steadiness of filament voltage which is necessary, would be helpful.

Mr. J. H. Reyner: One of the most interesting points raised is that of the standardization of valves. The multiplicity of valves existing in this country, all subject to different nomenclature, is one of the most bewildering and least desirable aspects of the radio industry. The general requirements are by now reasonably standardized, so that such a step would be quite possible. We require first a high-impedance valve suitable for the two purposes of high-frequency amplification and impedance coupling. A valve having an impedance of about 30 000 ohms is reasonably suitable for both purposes, although many high-frequency valves are made at present with higher impedances than this. Secondly, a low-frequency small power valve is required having an impedance of 6 000 to 7 000 ohms. Finally,

for general use, a general-purpose valve having an impedance of the order of 20 000 ohms would be desirable. These suggested three classifications are only tentative, and naturally some discussion would be necessary before any decision could be arrived at. For instance, dry-cell and accumulator types would be desirable in each class. The present state of radio technique, however, is such that quite satisfactory results can be obtained with the three types mentioned, apart from certain valves to fulfil special requirements. A point on which I am not quite in agreement with the authors is that of the method of testing the valves themselves. It appears that the valve is run, during its life-test, with the correct rated voltage on the valve. This is not a duplicate of practical conditions. What happens here is that the valve is run from an accumulator with a filament rheostat in series, and there is an increasing tendency towards the use of fixed resistances, which safeguard the valves and prevent overrunning. In such circumstances if the current taken by the valve during its life varies, the actual voltage on the valve itself will also vary. With a constant applied voltage on the valve, the current tends to decrease as the valve ages. If there is a resistance in series with the valve the voltage on the valve itself will rise accordingly. There may be a corresponding increase of current which tends to compensate for this, but I should like to have the authors' views on this matter. In view of the dependence of nearly all the characteristics on the filament voltage this appears to be a point worth considering. The suggestions raised by the authors for rating tests to be taken on valves are again interesting. In particular the suggestion made on page 971, that in order to ensure amply sufficient anode characteristics the expression

$$\left[\frac{\delta I}{\delta e}\right]_{e=+4}^{e=0} \nless \left[\frac{\delta I}{\delta e}\right]_{e=0}^{e=-4}$$

should be satisfied, is an interesting way of overcoming the difficulty, The valve quoted, however, would be discarded on this basis after 250 hours or less, which does not appear to be a very long life.

Mr. H. A. Thomas : The authors have produced a reliable method of testing valves produced in large numbers. Conformity to a given specification is always the test of the excellence of a commercial article, and in the case of a valve the precision of manufacture is such that the standard now obtained may be considered good. Yet much improvement is still necessary before the published characteristics can be considered to represent with precision the behaviour of the commercial product. The limit of 20 per cent, apparently now imposed, leaves much room still for development. It would be interesting to know to what type of valve Fig. 1 (*c*) refers, since the change of characteristic shown is extremely rapid. Have the authors carried out any tests on the nature of filament failure ? Life-tests on lamps have shown that failures take place at a weak spot on the filament ; the resistance rapidly increases and the filament diameter at the weak spot rapidly decreases until fracture. Does this failure take place at the negative end of the filament which is carrying the maximum current ? It would be interesting to know whether the life of a vertically supported filament is greater than that of a horizontally supported one.

Messrs. M. Thompson, R. H. Dudderidge and **L. G. A. Sims** (*in reply*) : Any value which our paper may have had in its original form has been considerably enhanced by the interesting contributions since made by others who are also intimately associated with valve-testing, and we are particularly glad to find that so many are in obvious agreement upon the desirability of ventilating the subject.

With regard to the use of alternating current for filament heating, we still think that in comparatively large installations this is considerably more convenient than the storage battery supply of direct current, while it will no doubt be readily conceded that it is also much more flexible than the d.c. generator system described by Mr. Goldup. It should perhaps be pointed out that when our installation was designed, quite a large proportion of the valves to be tested were of the bright tungsten filament variety, in which the normal cause of failure was a burnt-out filament. The use of the life-test circuit described by Mr. Clinker, with its series resistance common to 12 filaments, would have seriously prejudiced the results, since, for example, the failure of two filaments out of 12 would have brought about approximately a 5 per cent increase in the voltage-drop across the remaining filaments, the rate of decay of which would consequently have been doubled, until such time as the voltage-drop was re-adjusted. This advantage would, of course, be greater with a smaller number of valves in the batch.

Even with dull-emitter valves, the testing of an experimental batch in which a trial was being made of methods of applying filament tension might have been seriously complicated by the same effect.

The second point which has called forth considerable criticism is our suggestion that a measurement of I_e is not essential in any specification of life. This suggestion was made with the object of indicating the possibility of drawing up one type of specification embodying simple measurements which would be applicable to all the types of valve which are at present manufactured, or likely to be manufactured in the future. In point of fact we actually do take measurements of I_e on all the receiving valves tested on behalf of the M.O. Valve Company, and we agree with Mr. Goldup that with certain types of oxide cathodes similar measurements can be usefully made, but at the same time there are types of oxide cathode valves on the market in which such a measurement would, in our view, be perfectly useless. In such cases we have employed some other function, such as R_a or mutual conductance, as a criterion of stability of characteristics. In exceptional cases we have occasionally plotted the full anode characteristic curve at intervals during life; the curves of Fig. 1 (*c*), for example, were obtained from a valve which was tested at its rated voltages but which, we should perhaps explain, was not of a type manufactured by the M.O. Valve Co.

We were rather surprised to read Dr. Hodgson's repetition of the fallacious argument concerning the life

and temperature of different types of cathodes. In order to make clear the fallacy, it is only necessary to point out that an over-run dull emitter, although cooler than an under-run bright emitter, will give a shorter useful life. Examples in figures are as follows: Bright tungsten at 2 200° K. has a longer useful life than dull-emitting thoriated tungsten at 2 100° K., while thoriated tungsten at 1 900° K. has a longer useful life than an oxide cathode at 1 700° K. It is, of course, the stability of the emitting surface which is of decisive importance.

The criticism made by Col. Purves of the anode voltage figures which we gave by way of illustration of routine measurements is, of course, perfectly sound, and the figures in question should have been 90 and 110, as he suggests. In reply to another query, although most of our regular tests cease at 1 000 hours, we have at various times run tests for much longer periods, and a few types are regularly tested for periods varying from 5 000 to 20 000 hours. The latter figure, which represents about 2½ years' continuous running, has been well exceeded by samples of a valve-type designed primarily for telephone repeater use. We have no figures connecting the life of valves with the frequency of switching on and off. With regard to Col. Purves's last point, his requirements are in agreement with the view which we expressed in the paper, that when a valve is required to give satisfaction throughout a range of filament voltages, the life test should be conducted at the top, while the periodic measurements of characteristics, emission, etc., should be made at the bottom of the range.

Several contributors to the discussion remark upon the need for an experimental determination of the relation between life and temperature of short tungsten filaments. The relation quoted in the paper is well-established for the long filaments used in lamps, and our experience confirms that the same formula is closely applicable to the 10- to 20-volt filaments used in transmitting valves. Our life-test results obtained from the lamps used in mines (2 volts) and on motor-cars (6 volts), and also from small valves (4–6 volts) are certainly in very fair agreement with the same formula although it certainly cannot be claimed that some small adjustment to the value of the exponent to V would not be necessary for these short filaments.

There is one interesting point in the design of a life-test circuit which has arisen since the paper was originally drafted, which is that of self-oscillation occurring among a bank of valves running in parallel. This is more liable to occur when the valve is of a type having a high value of mutual conductance and was indicated in our case by the milliammeter, which is kept permanently installed in the grid bias circuit. Although all connecting leads are kept as short as possible, there is apparently sufficient inductance in the circuit to enable such oscillations to be set up. In our case the difficulty was overcome by connecting small condensers between the filament and grid terminals at the back of the valve sockets.

THE BENEVOLENT FUND.

28TH ANNUAL GENERAL MEETING, 27 MAY, 1926.

Mr. R. A. Chattock, President, took the chair at 5.30 p.m.

The notice convening the meeting was taken as read.

The minutes of the 27th Annual General Meeting held on the 7th May, 1925, were also taken as read and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1925 (see page 670) were presented, and, on the motion of the Chairman, seconded by Mr. P. Rosling, were unanimously adopted.

The Chairman proposed, and Mr. Roger T. Smith seconded, that Mr. J. Attfield, F.C.A., be re-appointed Hon. Auditor. The motion was carried unanimously and the meeting then terminated.

REPORT OF THE COMMITTEE OF MANAGEMENT OF THE BENEVOLENT FUND FOR THE YEAR 1925.

CAPITAL.

The Capital Account stood on the 31st December, 1925, at £10 004 11s. 3d., which is invested.

RECEIPTS.

The Income for 1925 from dividends, interest, and annual subscriptions was as follows :—

	£	s.	d.
Dividends on investments ..	493	16	5
Interest	13	1	8
518 annual subscriptions	327	0	0
	£833	18	1

In addition to the foregoing, the Fund benefited during the year by the following amounts, many of which are non-recurring donations :—

	£	s.	d.
I.E.E. Entertainment Fund	100	0	0
Electrical Engineers' Ball Committee ..	70	0	0
Birmingham and Midland Electrical Engineers' Ball Committee	26	5	0
W. T. Henley's Telegraph Works, Ltd. ..	25	0	0
Western Centre (collected)	22	2	8
" Twenty-Five " Club	21	0	0
W. B. Woodhouse	10	10	0
General Electric Co., Ltd.	10	10	0
Incorporated Municipal Electrical Association	10	10	0
F. R. Marsh	10	10	0
J. D. Dallas	10	0	0
Sir Alexander B. W. Kennedy	10	0	0
Sir George Sutton, Bart.	10	0	0
and 1 093 donations of under £10	542	15	11
	£879	3	7

The accumulated balance of the Income and Expenditure Account amounted on the 31st December, 1925, to £2 380 9s. 6d., of which £1 998 14s. was invested and £150 was on deposit with the Institution bankers.

DONATION TO CAPITAL.

The thanks of the Committee are due to Mr. C. P. Sparks, C.B.E., Past-President, for a special donation of £35 given by him in 1925 for the purpose of bringing the Capital Account of the Fund to over £10 000.

DONORS AND SUBSCRIBERS.

Lists of the names of donors and subscribers during 1925 have been published in the *Journal*.

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers, and to intimate that, apart from donations, the Committee will be grateful for annual subscriptions of any amount.

GRANTS.

Applications for assistance were made by or on behalf of 30 persons during 1925, and the Committee, after due consideration, made grants in all of the cases. The total amount of the grants was £1 199 5s. 1d.

WILDE FUND.

The Capital Account stood on the 31st December, 1925, at £2 949 6s. 7d., all of which is invested and brings in an annual income of £106 11s. 10d.

The balance standing to the credit of the Income Account, from which, under the Trust Deed, full Members only can benefit, on the same date was £111 18s. 7d.

A grant of £107 was made from this Fund during the year.

PROCEEDINGS OF THE INSTITUTION.

743RD ORDINARY MEETING, 8 APRIL, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 18th March, 1926, were taken as read and were confirmed and signed.

Messrs. E. T. Williams and R. Wightman were appointed scrutineers of the ballot for the election and transfer of members and, at the close of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Graduates.

Andrew, John Cardell P., B.Sc.
Baillies, Douglas C.
Lord, Bernard Stevenson.
Reeman, Herbert Frederick.
Smith, Charles Henry.
Smith, William.

Students.

Baldwin, Michael C.
Barker, Percy Landen, B.Sc.
Baynton, Ronald Alfred.
Bean, Leonard Carlin.
Blake, Ernest Cuthbert.
Bland, Leonard George.
Boul, John Edward.
Bowles, Charles.
Brunker, Alfred John.
Buck, Charles Leslie F.
Buxton, Henry Fowler.
Caine, Kenneth Ernest.
Clark, Reginald Erskine.
Couch, Percy Reginald.
Cowan, James Allan.
Deacon, Frederick James.
Duncan, Nigel Leigh.
Edgar, John Alfred.
Edwards, Eric Walter.
Elton, John Goodenough.
Fisher, Alexander.
Gillam, Gerald Hugh.
Graham, Malcolm Taylor.
Gray, Robert.
Groom, Francis Henry.
Hamilton, Thomas William.
Hancock, Eric Holland.
Handley, Eric Thomas.
Harvey, Robert Burrell.
Haskell, David Nissim.
Heath, Frederick Ernest.
Holt, Alfred Ifor W.
James, David Urmston.
Jarvis, William.
Kishk, Mohammed Mahmoud.
Klesel, Kenneth John.
Langdon, George Ellis.
Lewin, John Robert.
Lister, Edward.
Lovelock, Herbert Ralph.
McEwan, Ronald Grant.
McRostie, John Baxter.
Mallinson, William David.
Mason, Frederick Oliver.
Mawson, Spurgeon.
Mercer, Jonathan.
Merrick, Ernest Clifford.
Mildner, Raymond Charles.
Millar, Harold James.

Students—continued.

Mills, Harry Douglas.
Moffat, Henry James.
Murphy, James Thomas D.
Nash, Harold Arthur.
Neave, James William C.
Pearce, John Broyd.
Pritchard, Ronald.
Richards, Claude Langdon.
Rooney, James Louis.
Sage, Harry Edward.
Scott, Douglas Murray.
Sher, Wsewolod.
Small, Charles John P.
Sparrow, Leslie Francis.
Stebbings, Reginald William C.
Swann, Sydney Bernerd.
Thompson, Harold Norman.
Venables, Albert Henry.
Wearmouth, Albert.
Wellard, William John F.
Westaway, Edgar James.
Westlake, Cyril Maude.
Whittaker, James Edward.
Wilkinson, Charles George E.
Wolff, Frank Edward.

TRANSFERS.

Associate Member to Member.

Melsom, Sydney William.

Student to Associate Member.

Lovely, William Stanley, B.Sc.

Student to Graduate.

Ashton, Arthur Leigh, B.Sc.
Cunliffe, Cyril Henley.
Freeborn, Frederic Victor, B.Sc.(Eng.).
Howe, Reginald Percy.
Shearer, George, B.Sc.(Eng.).
Shepherd, Joseph Hubert.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 503) was taken as read, and the thanks of the meeting were accorded to the donors.

The following papers : "The Application of Machinery at the Coal Face," by S. Mavor, Member, "The Design of Storage Battery Locomotives for use in Coal Mines," by L. Miller, Associate Member, and "Electricity in Mines : A Short Survey," by R. Nelson, Member, were read and discussed.

On the motion of the President a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.55 p.m.

53RD MEETING OF THE WIRELESS SECTION, 14 APRIL, 1926.

Major B. Binyon, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 3rd March, 1926, were taken as read and were confirmed and signed.

A paper by Mr. E. H. Shaughnessy, O.B.E., Member, entitled "The Rugby Radio Station of the British Post Office" (see page 683), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

INSTITUTION NOTES.

Students' Premiums.

The Council have awarded Students' Premiums, each of the value of £10, for the session 1925–26 as follows :—

Author.	*Title of Paper.*
W. F. C. Cooper	" Some Experimental Work on Relays."
F. J. Lane, M.Sc.	" A Rotary-Converter Automatic Substation."
C. T. Melling, M.Sc.	" The Design of Current Transformers."
H. Pryce-Jones	" Electric Winding Engines in Collieries."
E. Youel, B.Eng.	" The Thermionic Vacuum Tube."

Public Works, Roads and Transport Congress and Exhibition, November, 1927.

The Congress Organizing Committee have decided to offer the following prizes for papers submitted for discussion at the Congress to be held in November 1927 :—

1st Prize—Gold Medal and £50.
2nd Prize—Silver Medal and £25.
3rd Prize—Bronze Medal and £10.

The subject of each paper must be one which falls within the services covered by the Congress, that is to say :—Highways and bridges, water supply, sewerage and sewage disposal, cleansing, gas, electricity, housing and town-planning, tramways and light railways, agriculture (small holdings, land drainage, land reclamation and agricultural education), and local government organization.

The prizes will be awarded to the authors of those papers which, irrespective of the subjects dealt with, are considered by the adjudicators to contribute most materially to the advancement of local government in the services covered by the Congress.

Application for the rules of the competition should be made to the Hon. Secretary, Public Works, Roads and Transport Congress, 84 Eccleston-square, London, S.W. 1, from whom more detailed information as regards the subjects for papers may also be obtained.

Papers must be submitted not later than the 17th January, 1927. Papers may also be submitted for discussion at the Congress without being entered for competition. Such papers should be clearly marked " Not for competition."

Regulations for the Electrical Equipment of Ships.

The Council have revised the I.E.E. Regulations for the Electrical Equipment of Ships and have authorized the publication of a Second Edition. Copies may be obtained from the Secretary, or from Messrs. E. & F. N. Spon, Ltd., 57 Haymarket, S.W. 1., at the following prices :—

Bound in blue cloth : 3s. 6d. net (or 3s. 8d. post free).
Bound in black American cloth : 2s. 6d. net (or 2s. 8d. post free).

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 July–25 August, 1926.

	£	s.	d.
Bechar, S. (Kharagpur, India)		5	0
Bentley, J. C. (Manchester)		5	0
Bogie, A. (Edinburgh)		3	6
Brumwell, W. (Parkstone)		7	6*
Caldicott, R. A. H. (Sibsagar, Assam)		10	0
Donovan, E. T. G. (Birmingham)		6	0
Grey, W. J. (Shanghai)	1	5	0
Hayhurst, H. (Sheffield)		10	0
Herbert, T. E. (Manchester)		5	0
Jones, J. R. (Houghton-le-Spring)		5	0
McKnight, W. A. (Providence, Rhode Island)		10	0
Middleton, W. J. B. (Nelson, Lancs.)		3	6
Milne, L. (London)		5	0
Moore, A. E. (Manchester)		5	0
Nagabushanan, S. (Tanjore, India)		5	0
Parry, W. (Altrincham)	1	1	0
Rigg, R. (London)		4	0
Scott, G. I. (Somerset)		5	0
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THE APPLICATIONS OF MACHINERY AT THE COAL FACE.

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SUMMARY.

The necessity for reduction in the cost and price of coal is considered, and the use of labour-saving machinery in the primary processes of winning coal is indicated as the most effective means by which the high labour cost can be substantially reduced.

The evolution and early history of coal-cutters are outlined, the later developments of these machines are indicated, and the leading characteristics of the bar, chain and disc coal-cutters are detailed.

The nature of the service required of coal-cutters is explained, and the conditions under which the service is rendered are defined.

Conveyors for underground use are described, and an outline is given of their place in the practice of intensive mining; first, in increasing the output per man at the coal-face, and, second, as an aid to the reduction of the cost of transport of the coal from site to the mechanical haulage.

An endeavour is made to indicate the respective spheres of electricity and compressed air for actuating coal-face machinery.

INTRODUCTION.

When it was suggested that I should prepare this paper it was proposed that it should deal with "The introduction of coal-cutting machinery of either the compressed air or the electrical type to avoid hand-hewing, and the most economical method of conveying the coal from the coal face to the main haulage roads either by conveyors or by other means." In the present condition of the coal industry this subject has more than technical and industrial importance. It is a matter of grave national concern; therefore there is no need to stress the opportuneness of such a paper. It is also appropriate that a paper on this subject should be included in the *Journal* of the Institution, because the great expansion of mechanical mining of coal not only in this country where coal-cutters were originated, but also abroad, has been due in large measure to the application of electricity to coal-face machinery. It may further be said that the electric coal-cutter has stimulated improvement in and use of compressed-air machines for the same service.

The mining industry of this country contains within itself the means of its own regeneration, and if relieved of legislative interference these means would become increasingly operative. It is impossible for anyone familiar with recent practice in mechanical coal-mining and with its economic results, to be otherwise than optimistic as to the future of the industry if the colliery owners and the miners are left to settle their own affairs. In mining, as in every other industry, the problem of cost reduction is that of increasing individual output, but in mining this problem has special significance because labour accounts for 75 per cent of the total cost of production, and because the higher this proportion the more effectively it can be attacked. Many palliatives of the existing situation may be suggested, but, apart from the number of working hours, the only way to effect substantial increase of output per man and consequent reduction of costs is the systematic application of labour-saving machinery. In other words, there are too many men in the mines; the number must be reduced, for the industry cannot afford to support them. The necessarily gradual nature of the process of adapting mining methods to the use of machinery will to a great extent avoid the imposing of individual hardship by reduction in the number of men employed. At many collieries modern coal-producing machinery is, even in these days of low prices, earning profits that without it would be non-existent. The condition of unsettlement and the sense of insecurity of recent years and of the present day, have seriously retarded progress in the equipment of mines with machinery of production, and have thus accentuated the difficulties of the present situation.

In England the proportion of machine-cut coal to the total output is, according to the latest Report of the Mines Department, 14 per cent, whereas in Scotland the proportion is 47 per cent. The geological conditions in Scotland are not more favourable to machine mining; the difference is due partly to economic pressure compelling a reduction in cost of production, but largely to the permissibility of electricity at the coal face in most of the Scottish mines. In Scotland 93·25 per cent of the coal-cutters in use are electric and 6·75 per cent are compressed-air machines. It is not generally realized that a very important factor in the rapid extension of machine mining in the United States is that the comparative freedom from gas in the mines renders electricity permissible, and it is noteworthy that in the most recent years the rate of increase in the proportion of machine-mined coal has been greater in Scotland than in the United States.

To the members of this Institution any technical means of reducing the cost of coal—the raw material of power production—must have lively interest, and to many of them it is a subject of vital concern. The Coal Commission, whose chief function was to ascertain how the cost of coal production could be reduced, had the immediate anomalous result of retarding the progress of the most effective means of reducing costs—the extended use of the machinery of coal production. The period of uncertainty and unsettlement that attended the crisis last autumn was continued by the

appointment and sitting of the Royal Commission and by the period of waiting for the Report. Under these conditions, the majority of colliery owners were disinclined to incur avoidable capital expenditure; much development involving all kinds of colliery equipment was therefore suspended, and, whilst the mines have urgent need for new machinery, the workshops that might have been making it were half empty, and operative engineers were added to the numbers on the dole.

Many papers have been presented to this and to other Institutions on the various problems of the generation and distribution of power at collieries and of its application to winding, ventilating, pumping, haulage and so on; all these papers have been concerned with what may be described as services. The surface equipment of many collieries is splendid, but underground, where the money is lost or made, the coal faces are crying out for machinery. This paper will deal with the application of power to the primary operations of winning the coal and conveying it from the immediate vicinity of the face—operations to which the whole surface and underground equipment and organization of the mine are secondary. The peculiar physical conditions under which these primary operations are conducted have an important bearing on the problems of applying power to coal-producing machinery.

In order to provide a background for what is to follow it is necessary to give a general but brief outline of the principal characteristics of the coal seams of this country and of the methods by which they are mined.

The Coal Seams and Methods of Mining Them.

The coal seams vary greatly in thickness, in depth from the surface, and in inclination from the horizontal, but it may be said that the output is obtained chiefly from seams between 2 ft. and 6 ft. in thickness, at depths between 300 yards and 800 yards, and at inclinations between zero and 15°. The geological associations of the coal seams also differ widely, and the seams may be clean, may contain bands of such material as fireclay or shale, or may be overlaid by friable material that falls with the coal.

Broadly it may be said that the methods of mining coal may be grouped under two systems: (1) The "pillar and stall" system, and (2) the "longwall" system: each of these has many variants, in some of which demarcation disappears.

In the "pillar and stall" system, which was the earlier, the coal is extracted in stalls, pillars of coal being left to support the roof, the width of stalls and the size of the pillars being determined by the superincumbent weight and the character of the roof. The first working is the forming of the stalls, and the second working is extraction of the pillars; where disturbance of the surface must be avoided, the coal pillars may be left to support the roof. Fig. 1 illustrates the system, which in this country has to a great extent been superseded by longwall mining.

The term "longwall" also is descriptive, for in this system (Fig. 2) the coal is exposed on a long face or wall that may be 50 yards long or 10 or more times that length. Advancing longwall is usual, i.e. as the coal is extracted the faces advance from the shaft towards the boundary. It will be seen that in this system the main and branch haulage roads, and the gate roads which give immediate access to the face, are formed and maintained in the areas from which all the coal has been extracted. In seams of a height that permits the trams to be taken along the face to be filled, gate roads that give access to the face are formed at distances of 20 to 40 yards apart; in thinner seams the gates are usually about 15 yards apart, and

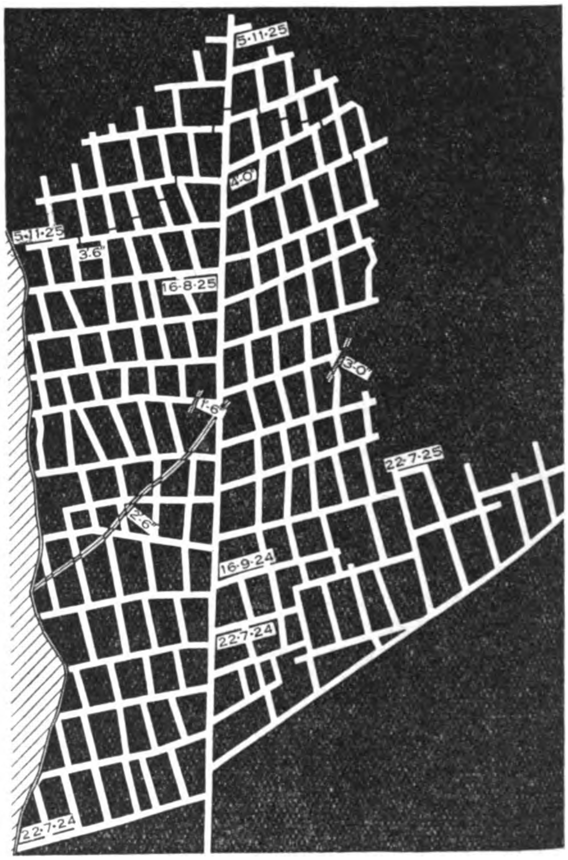


Fig. 1.—"Pillar and stall" system of mining.

the coal is cast by shovel to the gate-ends where the trams are filled.

In both systems the actual operation of mining the coal consists of cutting a slot in the coal usually at the floor-level; the coal, if strong, is then broken down by explosives or by wedges, or where it is friable it may collapse and is then shovelled to the trams.

It will be apparent that the application of machinery to the undercutting and conveying of coal from the working face in these two systems of working present quite different problems.

A coal-cutter for "pillar and stall" service is required to cut, to a depth of about 6 ft., a "place," in width between 9 ft. and 20 ft., and then to flit to the next place to cut again, and so on. A machine of the requisite power and strength is necessarily heavy, yet it must be extremely mobile and amenable to control.

Such machines are usually self-propelling and are flitted on the tram rails, but where the inclination of the seam is too great for safe flitting on wheels, the machines are mounted on sledges and fitted with gear for rope haulage. Collection of the coal by trams from a large number of " places " is a difficult problem; in thick seams the output from the individual headings may warrant the use of mechanical conveyors, but for the small output produced in the individual headings in thin seams, mechanical transport from the faces would not be economical.

For reasons quite unconnected with the use of coal-face machinery, longwall working has become general in this country, but this system happens to be favourable to the application of machinery both for undercutting and for mechanical conveying. As a very large proportion of the total output in this country is won by it, the longwall system and its mechanical equipment will now be dealt with.

The function of the coal-cutter is to undercut the face of coal. In one method of working, each machine has allotted to it such length of face as it can with certainty cut in one shift; on the next shift the cut coal is cleared, and on the third shift the roof in the gate roads is ripped to give height, the ripped material being used to build pack walls in the waste to support the roof. In the three shifts, i.e. in 24 hours, the complete cycle of operations is performed; on the next cutting shift the machine begins the same cycle of operations, cutting along the face from end to end in the opposite direction. This method is termed the " unit " system, and its working requires that the whole length of the face shall be cut on each cutting shift, and from the whole length of face the coal must be completely cleared on the filling shift. When rhythmical conduct of the operations is established, a definite daily output is obtained from each unit face. Failure of the machine to cut to the end of its face on any

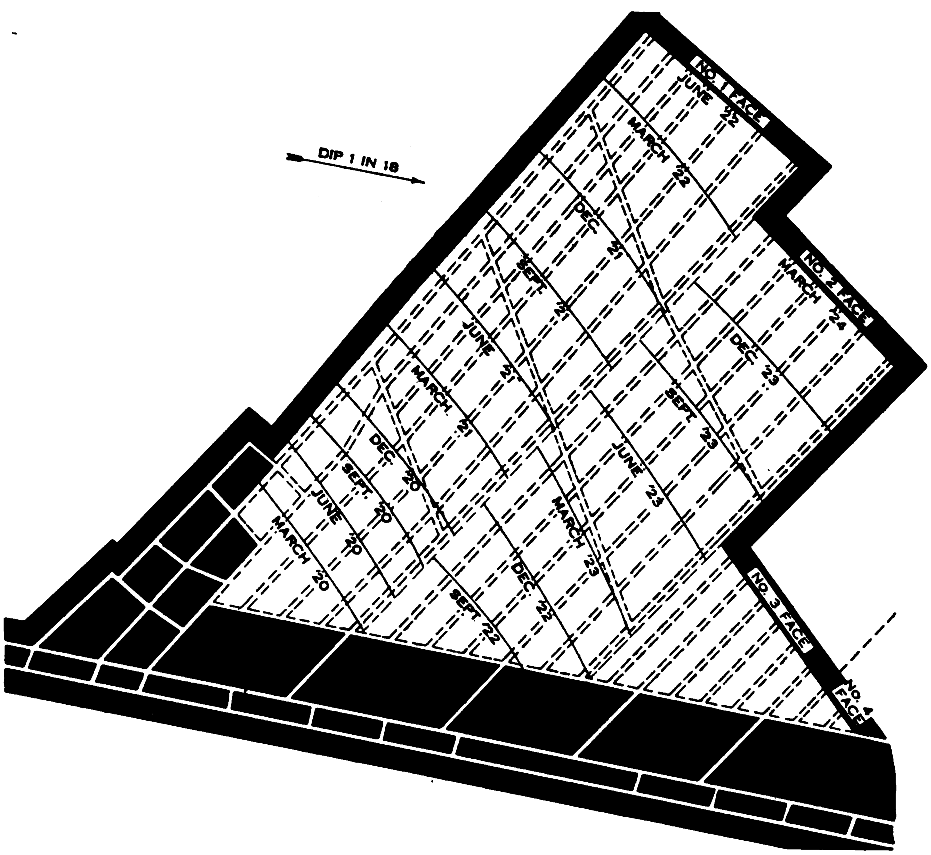


FIG. 2.—" Longwall " system of mining.

cutting shift would involve the loss of a day's output from the unit; no derangement of a machine, short of a complete breakdown, prevents its being driven to the end of the face.

The other method of applying longwall machinery is to open out an extended face a few hundred yards or many hundred yards in length; along the face two or more coal-cutters follow each other from one end of the face to the other, and each machine on reaching the end of the face is flitted on a trolley through the roadways to start again another cut along the face in the same direction. This method is general where the thickness of seam and the depth of cut produce more coal than can by the available means be cleared in

time to permit the machine to cut to and fro; cutting and filling may proceed simultaneously at different parts of the face. The machines can cut only when the coal immediately in front of them (cut by the preceding machine) has been cleared; the length of face available for each machine to cut is variable and so therefore is the work done by the machine and its crew. On one shift only a short distance may be available; on the next a long distance of cleared face may present opportunity for forcing the machine, and the crew paid by the ton. Those who may only have earned the minimum wage on the previous day are less concerned in driving the machine considerately than in increasing their earnings.

In the mining of coal seams by machines, the undercut is usually between 3 ft. and 6 ft. deep, according to the conditions, and is made in the plane of the seam. The slot or cut is not necessarily made in the coal; it may be made in the stratum immediately underlying the coal, or in the coal, or in a band of foreign material contained in the seam at any intermediate position between floor and roof, or above the seam, up to a height of between 4 ft. and 5 ft. from the floor. The purpose of the slot is to give relief, and so permit the breaking up of the seam by collapse of the coal, or by wedging or blasting it from the roof, or, in case of intermediate or overcut, by wedging or blasting it from the floor. The making of the slot by hand-picks is an irksome, laborious and, in thick seams, sometimes a dangerous task. The depth of cut made by hand rarely exceeds 3 ft., and to reach the back of even a 3-ft. cut the miner must hew clearance for his arms and shoulders and so a considerable amount of coal is broken up.

Evolution of the Mechanical Coal-Cutter.

Soon after the middle of the eighteenth century the problem of providing the pick man with mechanical aid began to engage attention. The earliest form of coal-cutter was the "iron man," so called because the aim was to simulate the operation of a manually wielded pick. The "iron man" was a contrivance which held a miner's pick, to which a reciprocating motion was imparted by a system of levers, power being applied through crank handles by two or more men. Many variants of the "iron man" were devised but, so long as the machine depended on muscle power, little progress was possible.

The first suggestion to discard the reciprocating pick in favour of continuously moving cutters was embodied in a patent of 1843 for a machine—the precursor of the disc coal-cutter—which was in effect a circular saw; but without adequate power to drive it such a machine could not succeed. It was not until after the middle of the nineteenth century, when compressed-air power became available for underground service, that development of the coal-cutter was possible. Compressed-air power was at first applied to energize the "iron man," the pick of which operated by percussion at a point, but it was soon recognized that the new power might be utilized to greater advantage than by restricting it to delivery of blows by an individual pick. The application of air power to the driving of a rotating disc with cutters fixed at its periphery was a revolutionary innovation, for it marked not only the change from reciprocating to rotary movement, and from a individual pick to a group of picks, but also marked a radical change in the principle of attack by the tool. The pick on the swinging arm of the "iron man" operated by the shattering effect of impact and penetration of its point; the picks on the rotating disc operate by sustained pressure along a line, removing the material by cutting or tearing it from the face attacked. The power available from the air motors could not be fully utilized by an individual pick on a swinging arm, but on the other hand the possibility of multiplying the number of cutters on the rotating disc, and of increasing the lineal speed of the cutters and their pressure upon the material attacked, could not be fully developed for lack of sufficient power in the crude air motors that were are at first employed.

The sixth decade of the last century was marked by important steps in the evolution of the compressed-air coal-cutter; and to the disc machine were added in 1853 the chain machine and, 10 years later, the bar machine; in both types the movement of the cutters was continuous. Yet the "iron man" made a brave struggle for survival, and persisted in a losing battle against its rivals, for, 10 years after the first application of air power to a disc machine, a patent was granted for a machine in which a compressed-air, steam, or water turbine operated a cam whereby, through a system of levers and springs, an arm carrying a pick was caused to strike the coal "with force at least equal to that which can be given out by the blow of a pick wielded by a man's arm." That the "iron man" held its ground for more than 20 years after power had been applied to the disc machine may be taken as evidence of the difficulties experienced by the early designers of coal-cutting machines.

Since the period referred to, the development of power, strength and cutting capacity in coal-cutters has been progressive, but the principles that are applied with such effect in present-day coal-cutters were embodied in embryo in the early disc, chain and bar machines which were all originated in this country.

Between the 'sixties and 'eighties of last century, those who devoted themselves to the problem of mechanical coal-cutting struggled against many adversities, not the least of which were due to inadequate power of the air motors, and to the unsatisfactory character of the power service. Many difficulties were due to failure to recognize the limitations of coal-cutters; tasks impossible to the machines of those days were attempted, and failure and disillusion were the result. Yet some enthusiasts were constant to their aim, and a few of them achieved results that rewarded their tenacity. The disc machine was the earliest to gain any measure of economic success, and its first effective rival was the chain machine.

A new era in the evolution of the coal-cutter was opened by the application in 1885 of electricity as the motive power. In 1863 a patent had been granted for a reciprocating pick machine to be operated, through a system of levers, by electromagnets; but even if such a contrivance had been practicable the means of

energizing it were not at that date available. The first coal-cutter to be driven by an electric motor was a bar machine invented by James Blackburn, a Yorkshire colliery manager. It is suggestive of the difficulties of the pioneers, and of the far from satisfactory results obtained from compressed air as a source of power for coal-cutters, that Blackburn in his original machine adopted the hazardous expedient of driving by a wire rope running along the face at high speed. This wire rope was driven by shaft and pulleys from a main haulage rope. The occasion for resorting to an electric motor was experience of the inconvenience and imminent danger that resulted when the wire rope at the coal face left its pulleys.

A Past-President of this Institution, Mr. Ll. B. Atkinson, was associated with the design and fitting of a 10-h.p. electric motor to this machine. The comparatively high speed of rotation of the cutter bar was a characteristic favourable to the electric drive; the results of the experiment were so promising that a machine was specially designed to be driven by an electric motor. It soon became apparent that the electric motor required protection from the dust and dirt in which a coal-cutter moves and works; moreover, the sparking brushes of the motors of those days were manifestly unsafe where gas might be present. Mr. Atkinson rose to the occasion by designing and building a completely enclosed electric motor, the first used for any purpose; this step was soon followed by complete enclosure of the gearing of the machine. The bar type was the first coal-cutter to be so enclosed.

As in the whole range of engineering the electric motor has had a beneficial influence on the design of every machine with which it has been associated—so with coal-cutters the application of the electric motor resulted in rapid advance in the development of these machines. The priceless advantage in the use of electricity, that the power can be easily and accurately measured, was quickly turned to account in coal-cutters and the power and strength of the machines were rapidly increased; the application of the electric motor to the disc coal-cutter, and later to the chain machine, followed its successful use in the bar machine. Complete enclosure of the gearing of both disc and chain machines followed the adoption of the enclosed electric motor.

Previous to the use of the electric motor the coal-cutter had been at a serious disadvantage because of the unsatisfactory power service provided by compressed air. In those days the efficiency of the compressed-air system was extremely low, and when the motors near the pit bottom and those near the main pipes were supplied with air, and after loss of pressure by pipe friction and leakage of air from joints and open drain cocks had done their worst, little pressure and volume were available at the coal-cutters, which were necessarily remote from the compressors. In consequence, many attempts to cut coal mechanically ended in failure and the machines were unjustly discredited.

As in so many other early applications of the electric motor, the power required to drive a coal-cutter was at first underestimated; this underestimate was the more serious to coal-cutters, especially to disc machines, at a time when the limitations of the machines in other respects were little understood.

The next notable advance was the application of the three-phase motor, and the credit for taking the first steps is due to Mr. Roslyn Holiday who, at Ackton Hall Collieries early in 1898, replaced the compressed-air motor of a disc coal-cutter by two 10-h.p. three-phase motors with wound rotors and slip-rings; later the slip-rings were removed and the rotor windings closed. In 1901 Mr. Holiday fitted three-phase motors, with wound rotors short-circuited, both to chain and to bar machines. The author believes that these were the first coal-cutters to be fitted with three-phase motors. Increasing recognition of the advantages of the three-phase system for colliery power service led to the installation of many three-phase plants, and coal-cutter makers responded to the consequent demand by incorporating three-phase motors in their machines. The first coal-cutters to be put on the market with squirrel-cage rotors were probably the three-phase bar-type machines produced early in 1903.

The compressed-air motors originally applied to the disc machine had single cylinders with reciprocating pistons. They were followed by twin cylinders side by side; this type was also applied to bar and chain machines and was in general use until the turbine was introduced. It still survives in some disc machines which continue to do good work where the undercut is not deep and the air supply is adequate.

Later Development of the Coal-Cutter.

The electric motor importantly influenced the design of the coal-cutters with which it was incorporated; the possibility it introduced of developing large power in small dimensions resulted in the design of the whole machine being made more compact. The axis of the crank shaft of the compressed-air motor was across the coal-cutter, whereas the rotor of the electric motor, which was too long to be arranged crosswise, had to be placed in the long axis of the machine; this and the high speed of the electric motor, compared with that of the compressed-air motor, required complete redesign of the coal-cutter, with the cutting member as already developed and the electric motor as the bases of the design. The necessity for compliance with the principal dimensional characteristics of the electric motor resulted in a degree of uniformity not hitherto existing in the leading features of the designs of coal-cutters of the various types and by different makers.

Modern coal-cutters thus conform generally to the stabilized types illustrated in Figs. 3, 4 and 5, on which the principal components, the gearcase to which is attached the cutting member, the motor and the haulage gear, are indicated by the letters "A," "B" and "C."

For convenience in manufacture the overall dimensions of the d.c. and a.c. motors were made alike and with identical facings, so that either type of motor could be assembled in a coal-cutter; this interchangeability is an advantage to the user who may have occasion to change the system of power supply. Standardization having been carried so far, it became obviously desirable that the compressed-air motor should be brought into conformity with the new general design of the coal-

cutter; this involved approximation of the compressed-air motor to the size and shape of the electric motors. The compressed-air motors designed for the purpose indicated were short-stroke, high-speed, single-acting motors of the 3- or 4-cylinder type actuating a crankshaft in the long axis of the coal-cutter. Motors of this type and form were made to be interchangeable with the electric motors in the coal-cutter structure.

These air motors gave good service, but, owing to the necessary lightness and delicacy of their fast moving parts, they were not well suited to the rough usage and strenuous service to which they were subjected.

Another important step in the evolution of the coal-cutter was marked by the advent of the so-called "air turbine" motor. This motor consists of a casing in which twin hollow cylinders are formed; within the cylinders are two rotors on the surfaces of which are cut double helical teeth, the teeth of the opposing rotors meshing with each other as helical gear wheels; cylinder heads closing the ends of the cylinders carry ball bearings which support the rotor shafts. Air under pressure is admitted at the bottom of the casing through a port which opens on the apex of the teeth and fills the spaces between the teeth that are opposite the port; the pressure of the air forces the teeth apart, so causing the rotors to turn; as the rotors turn, the spaces opposite the port are in succession filled with air under pressure, the apex of the space in one rotor recedes from the apex of the tooth on the other rotor that engaged with it, and so the space is enlarged and the imprisoned air, while expanding, continues to do work until released at the ends of the rotors where the spaces are opened in succession by disengagement of the teeth.

The power is developed by the cumulative effect of the pressures in the spaces acting against the teeth of the opposing rotors and forcing them apart. It is essential that the teeth of the two rotors shall engage so closely that their lines of contact shall make practically airtight joints. The motor is extremely simple and robust, but it depends for its economical use of air upon a high order of precision in manufacture and upon accuracy of its adjustments.

This type of "turbine" was the subject of a long-expired British patent which probably brought no profit to its inventor, because the machine tools and engineering methods of his day could not approach the requisite accuracy. So the invention remained dormant until the development of engineering practice enabled an American firm to produce a satisfactory motor. The suitability of this type of motor for incorporation in the coal-cutters that had been adapted to the electric motor was apparent.

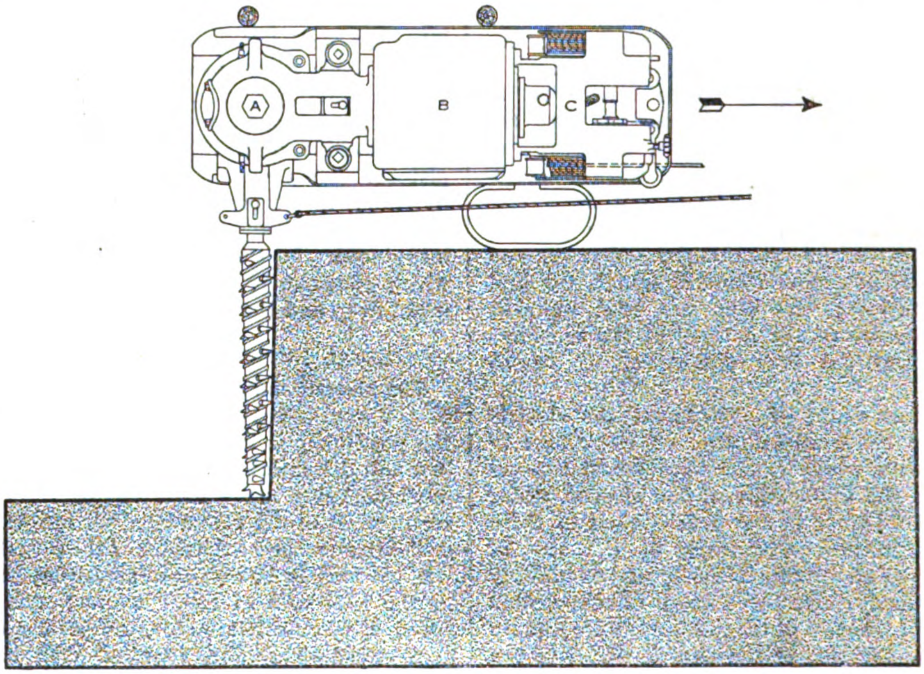


FIG. 3.—Bar type of coal-cutter.

In 1912 some American coal-cutters fitted with air turbines reached this country. They were at first regarded with scepticism; their economical use of air was doubted, and so was the suitability for coal-cutter service of machines which required delicacy of adjustment of their parts. The doubters were confounded, for air economy at least equal to that of the best reciprocating motors was demonstrated, and, in respect of reliability in service, experience proved their superiority. In the result the reciprocating motors were soon superseded by turbines in all modern British coal-cutters, and the simple rotary motion, which has ousted reciprocating motion in so many spheres, scored another triumph. Its advantages for coal-cutters are decisive.

The design of electric motors for coal-cutters is

subject to many limitations. D.C. motors which were first applied were favourable to the development of relatively high power in limited height because it is possible to use a rectangular and oblong cross-section, giving a flat and comparatively wide machine with its height as its least dimension, and extending laterally and longitudinally to dimensions that are less rigidly restricted. With a.c. motors, in which the magnetic and electrical elements are necessarily circular in form, the difficulty of the problem of meeting demand for equal power within the same limit of height as in the d.c. machine will be apparent.

In the case of industrial electric motors, the maximum output which can be obtained from a given size of motor shell is limited in the case of d.c. machines by the permissible temperature-rise at the end of a full-load run for a specified period, and by the maximum current with which the commutator can deal without sparking. For a.c. motors the temperature-rise is the controlling factor; the question of commutation does not arise. Secondary considerations must be taken into account in determining the size of shell to be used; it must be so chosen as to give an efficiency and, in the case of a.c. machines, a power factor not less than the recognized standard for the given output.

The conditions are entirely different in the case of

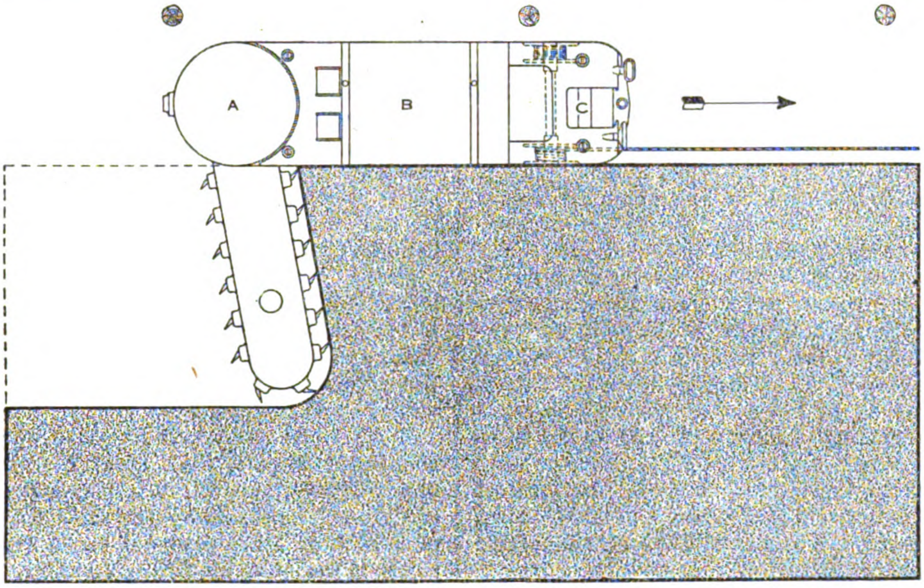


FIG. 4.—Chain type of coal-cutter.

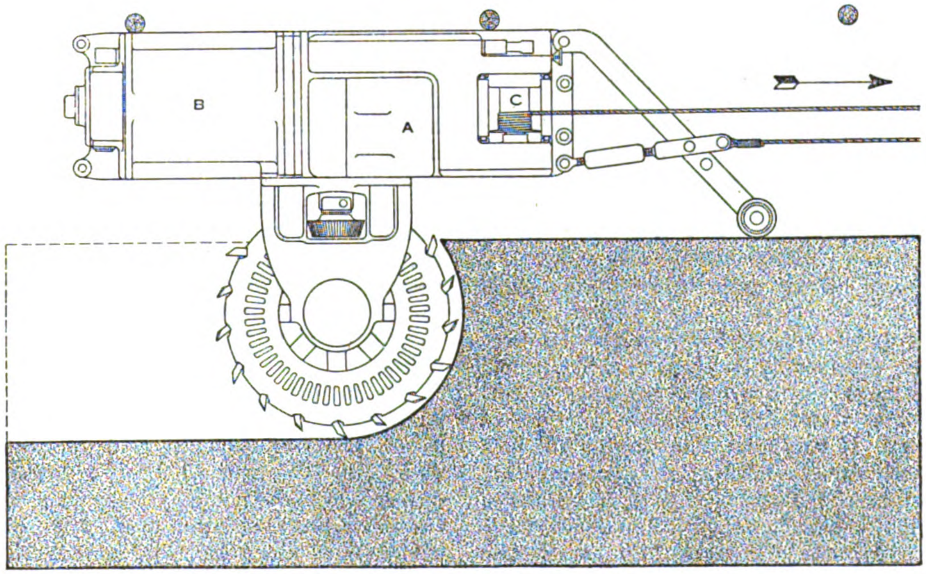


FIG. 5.—Disc type of coal-cutter.

motors to be used in coal-cutting machinery. There the dimensions of the motor are strictly limited by the conditions of service of the coal-cutter in which the motor is to be incorporated; the height especially is rigidly fixed, and this determines the maximum diameter of the armature or rotor. The problem is therefore presented to the electrical designer from a totally different aspect, and the ordinary canons of electric motor design cannot be applied. In the case of the normal industrial motor, with stated speed, output and voltage of the motor, the designer is required to determine the size from which he can obtain the best electrical properties; in the case of the coal-cutter motor, which is not a normal machine, he is confronted by precise limitations of space, the speed is determined by mechanical considerations, and he is required so to utilize the restricted space that the greatest possible horse-power is obtained. The work done by a coal-cutter is intermittent and may fluctuate violently from instant to instant, and the machine is liable to demand from its motor very large increases of power for brief periods, as when the cutters meet some obstacle, or when the overlying material collapses on the cutting member and jams or tends to jam it. The words "greatest possible horse-power" should therefore be interpreted to mean the greatest power that the motor will give without breaking down or ceasing to function, and should have no connection whatever with temperature-rise.

The limiting condition in the d.c. motor is commutation; when the load rises excessively, sparking occurs and may ultimately flash over from brush to brush. In the a.c. motor the limit is much more definite; it is the current at which the motor stalls. This current can be predicted from the design within fairly narrow limits.

The d.c. motor will accordingly be designed in the first place to have the best possible commutating properties. The a.c. motor will be designed to give the largest practicable stalling torque; other electrical properties will be ruthlessly sacrificed to this dominating requirement, and as a consequence the a.c. motor of a coal-cutter presents wider departure from normal design.

These essential points having had first consideration, it remains to the designer so to proportion the copper and iron in the motor as to get the smallest possible loss, the number of watts lost being the measure of the heat generated. If he succeeds in making the best possible use of the space available, and in providing for a maximum rate of dissipation of heat, he will have turned out the best coal-cutter motor, but he will have sacrificed many normal characteristics of electric motors and will have made many compromises between the desirable and the attainable. The temperature-rise of the motor at the end of any working shift will depend on the degree of skill exercised in driving the machine, on the depth of undercut, on the nature of the material being cut, on the condition of the cutter picks, and on the greater or less intermittency of the work.

Apart from the necessity for restricting the length of the machines, simplicity and robustness are so important in coal-cutter motors that in three-phase machines squirrel-cage rotors are generally used, although for disc machines, and in some cases for chain machines, wound rotors would have advantages. The stators of some machines are switched straight to the line, whilst others are wound for star-delta switching. Electricity supply at most collieries is on such a scale that no trouble is experienced from the high starting current required by individual coal-cutter motors. The circuit breakers on feeder cables to coal-cutters are set with a suitable time-lag—for example to trip in 10 to 15 seconds with the overload determined. The E.M.F. for which coal-cutters for service in this country are wound varies from 400 volts to 550 volts. The objections to lower pressure, especially for the larger machines, are (1) the weight, unwieldy character and increased liability to damage of the trailing cable that would be required, (2) the difficulty of allotting space to the larger switchgear, (3) the difficulties of winding, added to the existing limitations of winding space, and (4) the difficulties due to heavier sections of stator bars and the accommodation of windings suitable for different voltages and frequencies.

There is no recognized standard of power rating of coal-cutter motors, each maker's rating is individual and arbitrary, and, whilst it may serve for comparison of different machines by the same maker, the absence of a uniform basis prevents useful comparison of the rating of machines by different makers.

Characteristics of Bar, Chain and Disc Coal-Cutters.

For reasons that cannot be fully described here, the mean and the maximum powers required by the bar type (Fig. 3) are less than for the chain and disc types, the chain type (Fig. 4) is next in order, and the greatest mean and maximum powers are required by the disc machine (Fig. 5). The cutter bar of the bar machine is armed throughout its length with spirally arranged cutters; when it rotates, a reciprocating motion in its own axis and exceeding the axial distance between the cutter points is also imparted to it; the bar is thus surrounded by a zone bounded by the cylindrical or (with tapered bar) conical surface described by the points of the cutters in their combined circular and reciprocating motion.

The cutting member of the bar machine is by this characteristic enabled to follow irregularities of contour in the plane of advance, and to accommodate itself to irregularities of the floor of a seam or of a band of dirt in which the cut may be made; moreover, neither the resistance to rotation of the bar, nor the progress of the machine along the face, are affected by collapse of the coal or other material immediately behind the line of the cut. Owing to the large number of cutter picks of the bar machine, the comparatively small bite taken by each pick, and the immunity from liability to jamming of the cutting member, the power required by the bar machine varies less from the mean than in the other types.

The cutting member of the chain machine consists of a rigid jib round which a "race" is formed to guide the chain that carries the cutters. The cutter picks of the chain machine are fewer in number, and individually

they take a bigger bite than those of the bar machine. From the illustration it will be seen that the chain jib presents surfaces of considerable area in the space that has been undercut; if the cutters, for example, when they are improperly formed or adjusted or when they are worn, do not make adequate clearance, the jib may be jammed and the machine subjected to overstrain; or the same result may attend collapse of the material being undercut. It will also be seen that the width of the chain jib in the plane of the cut renders difficult any changes in contour of the cut to conform to an undulating floor. These characteristics of the chain machine are liable to impose on the motor considerable overload for periods of greater or less duration.

The cutting member of the disc machine presents a still larger area in the plane of the cut, and the attendant difficulties described in relation to the chain type are much accentuated; as the disc machine is less amenable to manœuvring than either of the other types, it must therefore overcome difficulties by frontal attack and must be endowed with great reserves of strength and power. The foregoing remarks on bar, chain and disc machines do not refer to the order of merit of the machines, each of which has its sphere, but only to characteristics that have special bearing on the power of the motors.

Coal-cutters are required to cut, not only in coals which in different seams vary widely in constituents and in physical structure, but also in strata adjacent to, or contained in the form of bands in, the coal seams; these strata are usually fire-clays, shales, etc., containing gritty matter in greater or less proportions and, not infrequently, layers or nodules of ironstone or metal pyrites. None of the known methods of measuring comparative hardness, when applied to materials of the kinds referred to, is of any value for the determination of comparative "cuttableness." With modern coal-cutters the "cuttableness" of any material depends on the endurance of the cutter picks, which are made of high-carbon steel hardened and tempered to suit the nature of the material to be cut. Where the material to be cut is highly resistant to penetration by the cutters, the pressure of the cutters against the material must be correspondingly increased; the point of the cutter, which moves at high velocity, may then become heated to a degree that softens it, with the result that the point is quickly worn off and the cutter no longer cuts.

It is clear that under such conditions a comparatively massive cutter, apart from its greater strength, has greater capacity for absorption of heat and will endure longer than a cutter of smaller mass. The massiveness of its cutters is one of the characteristics to which the disc machine owes its superiority in the hardest cuttable materials. The chain machine for a similar reason has in hard materials an advantage over the bar type.

The limits of the field of usefulness of coal-cutters cannot be defined with precision; they are elastic and have been widely extended by development of the capabilities of the machines. It may be said, however, that the respective types—bar, chain and disc—have comparative limitations imposed by the mining conditions. This subject cannot be treated at length here, but the following may be given as examples of mining conditions that impose limitations: Hardness of the material to be cut, presence of hard foreign bodies such as ironstone or pyrites at the holing position, friableness of the material under which the cut is made, the height from the floor at which the cut is required, undulations of a very hard floor, weakness of the roof of the seam, steepness of inclination of the seam, occurrence of faults or hitches in the seam, and so on. When it is considered that the cutting member of the disc machine—the disc—presents a large surface in the slot being cut and in the plane of advance of the machine; that the cutting member of the chain machine—the chain jib—presents a less surface, and that the bar machine presents only the bar, in effect a line, and that is entirely armed with cutters—the nature of some of the limitations of the respective machines may be understood.

A factor that limits the application of all machines, but in different degrees, is the hardness of the material to be cut, or rather the effect of the material on the cutter picks.

Conditions of Service of Coal-Cutters.

Coal-cutters are portable machines in a special sense, for the feed of the cutter picks is applied by advance of the whole machine along the face. While in operation the machines are in continuous movement, on rough floors which may be inclined from the horizontal between zero and 60° or more, in closely confined spaces, in more than semi-darkness, in floor water or under roof water, or in an attending cloud of dust, and driven by a rough-handed class of men whose familiar tools are pick and shovel. It will probably be agreed that in the whole range of services to which electric motors are applied none is more exacting than the driving of coal-cutters; and it will be clear that the design of these machines presents problems of more than ordinary difficulty. The pressing demands for maximum power, strength, rigidity and durability, all to be fulfilled within severely limited dimensions, and with flame-proof enclosure combined with ready access to the working parts, and over all the dominating essential of reliability, impose on the designer many compromises between desirable but mutually antagonistic characteristics. Features important in the views of the mechanical and the electrical engineer must make concessions or sacrifices to insistent demands by the mining engineer who does not always appreciate that fulfilment of his requirements in one direction implies his acceptance of limitations in another.

Many attempts have been made to produce coal-cutters; the small number of makers who have emerged successful—they can almost be counted on the fingers of one hand—is a measure of the difficulties of the problem. The successful machines have been evolved by the slow and costly—costly alike to the maker of the machine and to the colliery owner—process of trial and error, under actual service conditions. Coal-cutters of to-day are highly specialized machines; they are designed with less regard to the duties to be performed than to the abuse to which they will be subjected; selection and treatment of the materials of the component parts is based on experience of the

degree of durability of the respective parts in past service, and in selection full advantage is taken of recent advances in metallurgical science; the methods of precision and the machine-tool equipment employed in the production of coal-cutters are in line with the highest developments of modern engineering practice. The period of apprenticeship of the coal-cutter has expired; shortcomings and defects that formerly were condoned are no longer tolerated. The more the coal-cutter takes its place in the general scheme of mining, the more important becomes its reliability in service, for the greater is the responsibility placed on it. Where the mining conditions are favourable and systematic coal-cutting has been established, the machine takes the primary part in a cycle of operations organized to time table for production of 70 to 150 tons per shift, and in which 20 to 50 men (according to the seam conditions) may be engaged. The penalty of failure of the machine to fulfil its part is disorganization of the whole scheme, suspension of the correlated operations, loss of wages to the men, loss of output and serious increase of costs to the colliery.

In machines the working load of which depends so much on the personal factor in the driver, the electric motor has advantages and disadvantages. Coal-cutters with blunted cutter picks are often cruelly over-driven by careless or inexperienced men, and the willing electric motor responds by maintaining its speed and developing more and more power up to the limit of its capacity—power which is wasted in grinding away the picks and in wear and tear of the overstressed mechanical parts of the coal-cutter. With the compressed-air system applied to the driving of coal-cutters the b.h.p.-hours required to be delivered to the compressors is roughly between four and five times that required to be delivered to electric generators for an equal amount of useful work done by coal-cutters. This relatively low efficiency of compressed air is partly inherent in the system as applied to colliery service, and partly due to the conditions under which coal-cutters are used. Wherever considerations of safety do not preclude the use of electricity for coal-cutting, electricity should always be adopted. There are, however, a large number of collieries in this country where there is no alternative to compressed air and its indispensability condones its relative inefficiency. Generally, compressed-air power systems are much less efficient than they ought to be and might be, because engineers in charge have not yet acquired the habit of measurement that has so importantly contributed to efficiency in electrical engineering. At many collieries, alongside electric generating plant with switchboards loaded with measuring instruments, powerful air-compressors are at work with no other instrument than a simple pressure gauge. There are now a number of exceptions but, generally, compressed air is sent underground without being measured, and there is no check upon extravagance in its use or waste. Reliable air meters of the indicating, integrating and chart types are available, but at comparatively very few collieries are they used, and often not even a pressure gauge is to be found below ground. The neglect of measurement is the more serious, because in every compressed-air system in colliery service there is a pernicious tendency towards inefficiency, which can only be restrained by unremitting vigilance. The liability of the long ranges of piping to disturbance by movements of the strata and to rough treatment incidental to road repairs, is the source of much loss of volume by leakage, and the overloading of existing pipe ranges by adding motors, and the extensions of piping as the coal faces recede further and further from the pit bottom, are the frequent causes of extravagant loss of pressure. Leakage in the case of pressure air does not burn like steam, nor give shocks like electricity, and defects or derangements in the compressed-air pipe system may be economically very serious without compelling their repair. The development of defects may be so gradual and insidious as to escape detection, until the dwindling effectiveness of the air-driven machines and the consequent decline in coal output develops a crisis; repairs are then effected and the process of decline begins again.

Coal-face machinery, being the most remote from the compressors, is most affected by fall in the efficiency of the power supply. It may be said that the conditions under which coal-cutters are required to work impose upon compressed-air machines low efficiency in respect of air consumption. It is easy to design an air motor which will be economical in its use of air when worked under stated conditions of air pressure, rotor speed, and load. In coal-cutter service there are no standards of pressure, speed, or load; these conditions are all variable to wide limits, yet the machine is expected to go on with its work. The air pressure may vary or fluctuate during a shift between 70 and 30 lb. per sq. in., and the motor must be large enough to drive the machine at the low pressure. Fulfilment of this condition not only involves extravagant use of air at higher pressures, but also renders possible excessively high motor speeds and development of greatly increased power, and the whole machine must be capable of withstanding the consequences.

When the air pressure varies, the motor speed and the load are at the discretion of the machine-man, who has little regard for economy of air, and seldom much consideration for the machine as a piece of mechanism. The air consumption of a motor is more nearly proportional to the number of strokes of the pistons or revolutions of the rotor than to the useful work done, and if when the pressure is high the motor is allowed to race, it may swallow more air when running light than when fully loaded at normal speed. The air consumption per square yard undercut by a given machine depends on the rate of cutting; the faster the cutting speed the fewer revolutions will the rotor make while the machine cuts a square yard, and the less air will be used. The rate of cutting depends on many factors external to the machine—the conditions of the roof and floor of the seam affect the rate of progress, so do the hardness, toughness or brittleness of the material being cut, the form, condition and adjustment of the picks, and the personal factor in driving the machine.

It will be understood from the foregoing considerations that, apart from the inherently low efficiency of the compressed-air system, the conditions of use of coal-cutters depress the air efficiency of these machines below

that of, for example, pumps working at constant speed and load.

Fig. 6 compares the energy used by compressed air and electric coal-cutters tested under similar working conditions. The two curves are drawn to the same scale of energy, the compressed air and the electricity delivered to the machines being reduced to the equivalent horse-power-minutes. The curve of the electric machine may be taken as characteristic of all electric coal-cutters; that of the compressed-air machine in shape and in position on the scale is individual, but it roughly represents compressed-air machines in general. The curve of the compressed-air machine reveals how largely air consumption depends on skilful driving and how important it is by attention to cutter picks, etc., to enable the machine to travel as fast as practicable while working.

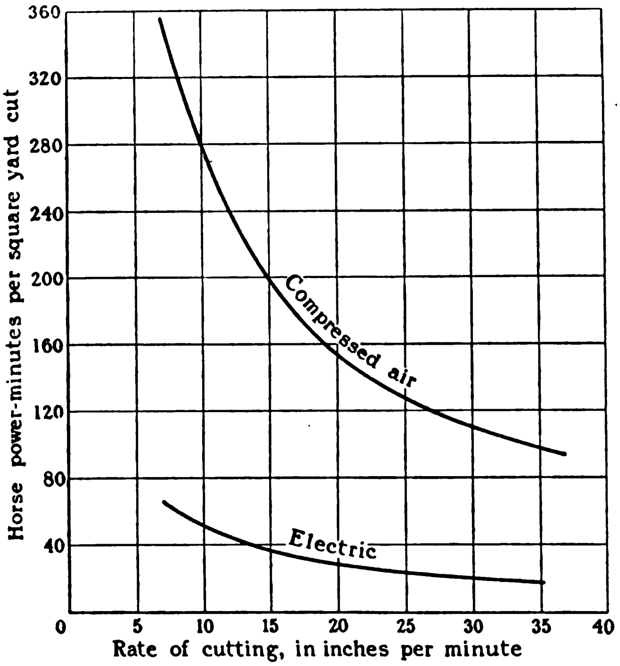


FIG. 6.—Energy used at various rates of cutting by compressed air and electric coal-cutters.

The b.h.p. rating of coal-cutters is arbitrary; the rated powers of the machines in most general use are between 20 b.h.p. and 50 b.h.p., but all have large overload capacity for short periods, and not infrequently they are required to develop it.

Under normal conditions the energy delivered to electric coal-cutters per square yard undercut varies from about 0·2 kWh in the most easily cut materials to about 1·0 kWh in the hardest cuttable materials. The average may be taken as 0·4 to 0·5 kWh. For the reasons already described, the equivalent in the case of compressed-air machines is much higher, especially in the case of harder materials.

MECHANICAL CONVEYING AT AND NEAR THE COAL FACE.

The application of power to the conveying of coal at and in the vicinity of the coal face may be described as technically and economically essential to intensive mining in which the productive effort is concentrated and large outputs are obtained from comparatively small areas. Coal-cutters increase largely the yield of coal per lineal yard of face per day, and, if full advantage is to be realized from the machines, the coal produced must be promptly removed from the faces. The workings of most existing collieries are laid out for hand-mining, and the arrangements of gate roads to the face, and of haulage roads (Fig. 2), are designed to deal with a comparatively small output from each working place. The introduction of coal-cutters to formerly hand-worked faces, by largely increasing the output to be loaded and drawn in a given area, puts excessive strain on the organization for distribution and collection of trams to and from the gate-ends. That the difficulties of dealing with the output from coal-cutters, without radical change in methods of loading the coal and delivering it to the mechanical haulage, are practically insuperable is becoming more widely recognized.

Many of the considerations that affect adoption of mechanical conveying cannot be referred to here, but two main functions of the system may be presented. First, conveyors laid along the coal face greatly accelerate the rate of clearance of coal from the face, and also increase substantially the output per man. Referring to Fig. 2, in thin seams the coal must be shovelled along the face, breaking it and often dirtying it in the process, to the gate-end where height is ripped to permit filling the coal into the trams. The coal is usually lifted by shovel and cast three times; the loading of 5 tons into a tram at the gate-end is thus approximately equivalent to shovelling 15 tons on to a face conveyor. In thick seams the trams are manhandled on rails laid along the face. Secondly, the collection of coal from face conveyors, by conveyors laid in gate roads (at intervals, for example, of 100 yards from each other), and its delivery to trunk conveyors from which the trams are loaded. The first of these functions affects face costs, and the second transport costs; the latter is often the more important. Consider, for example, that to get from a seam 3 ft. thick, 750 tons per filling shift, of coal undercut by machine on the previous shift, by the system illustrated in Fig. 2 it is necessary to supply to the face about 1 500 trams—20 to each of 75 gate-ends, and so to maintain the regularity of supply and withdrawal of the trams that the work of the men of the face shall not be delayed.

The system shown in Fig. 7, which illustrates a double unit with face conveyors to right and left delivering into a gate-end loader, or into a gate conveyor, reduces the number of tram loading-places from 75 to 4. If still fewer loading-places be desired the number can be reduced to 2, or even to 1, by a variant of the arrangement shown in Fig. 8; by this arrangement the face conveyors deliver into gate conveyors which from right and left convey to a trunk conveyor in the mothergate. The starting and control of such a group of compressed-air conveyors is simple, but it will be appreciated that the switching and cable arrangements for control at the discharging-end of the mothergate conveyor, of the individual motors on the electric power system, presents a somewhat special problem.

The plans referred to are typical of actual practice. Applied on the methods indicated, mechanical conveying contains the solution of the problem of avoiding the delays inherent in the system of loading individual trams at the face and manhandling them individually through gate roads to the mechanical haulage.

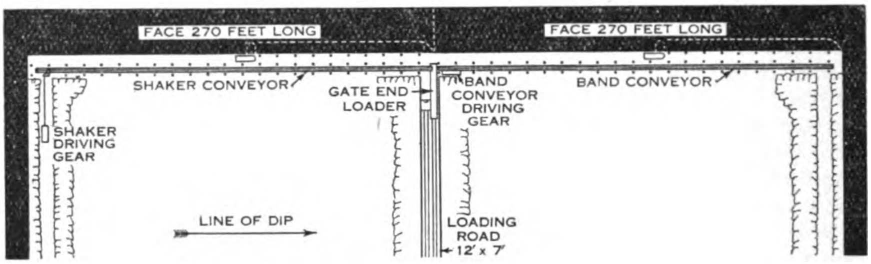


FIG. 7.—Double unit with face conveyors.

Individual face conveyors are usually of length between 75 and 150 yards; in gate roads greater lengths are not infrequent and trunk conveyors may extend to several hundred yards. The principle governing the use of conveyors for collecting is that the maximum daily output per yard of coal face shall be obtained, and that the lay-out of the faces and gates—subject to the mining conditions—shall be such that the desired output shall be delivered to the tram loading position by the minimum length of face and gate conveyors.

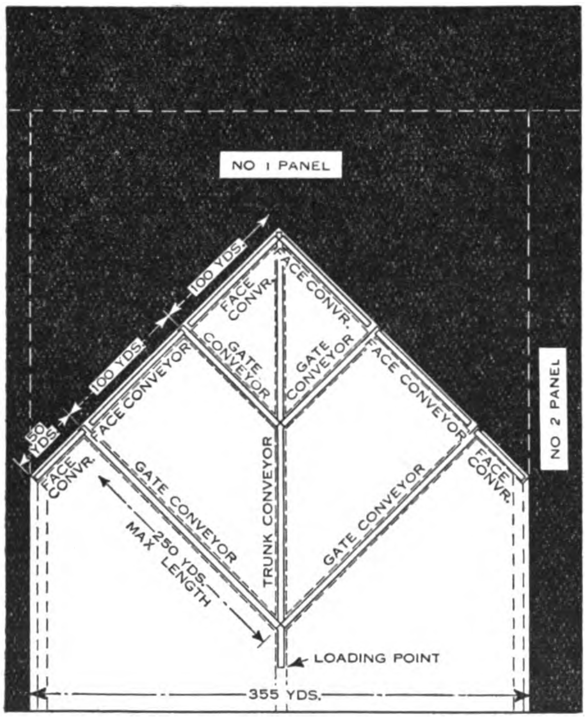


FIG. 8.—Gate conveying for collecting from a number of face conveyors to a single loading point.

The conveyors used for the purposes indicated are of three types, (*a*) the shaker or jigger, (*b*) the chain scraper, and (*c*) the band (a textile band usually faced with rubber). The scraper and the band types are unidirectional in operation and, apart from limitations of space, which are less stringent than in the case of coal-cutters, the application of electric motors to these machines does not present special difficulty to those experienced in the design of coal-cutter motors. The driving of the shaker conveyor, however, presents special problems. It is unnecessary here to refer in detail to the relative advantages of the three types; experience has allotted—without rigid demarcation—to each type its own sphere, and only where the mining conditions approach the border line between these spheres is there doubt as to choice of type. The sphere of one type or other may be extended by improvement in conveying capacity, or by mitigation or removal of disabilities.

Chain scraper and band conveyors are used where the gradient is against the load, and the band where the volume of coal to be conveyed is beyond the capacities of the scraper and shaker. In respect both of volume and of distance conveyed, the capacity of the chain scraper is comparatively limited; for trunk-conveying of volumes over 300 tons per shift for distances over about 200 yards the band type conveyor, the capacities of which in regard to volume and distance are limited only by economic considerations, will hold the field. Special conditions such as inclination, and special circumstances, may determine overlapping of the normal spheres of the respective types.

The shaker conveyor which was originated on the Continent is by far the most widely used of underground conveyors. Its special sphere is where there is a gradient in favour of the direction of delivery, but it is largely and successfully used on the horizontal and even against small gradients. It cannot be said that the possibilities of the shaker type of conveyor have yet been fully exploited, but restrictive elements inherent in the type will probably prevent any considerable extension of its already demonstrated capabilities in respect of conveying capacity on the level and against gravity respectively. The possibilities that remain are chiefly concerned with the characteristics of the appliance, whether actuated by electricity or compressed air, that imparts the reciprocating motion to the trough.

The shaker conveyor was first applied in steep seams. It was preceded by a line of stationary troughs on such inclinations that the coal cast into the troughs was

conveyed by gravity to the loading level. Where the troughs were used on gradients just insufficient to enable gravity to keep the coal moving downhill, a slight shaking movement of the trough was applied to aid gravity in overcoming the inertia, friction, and "stiction" of the coal and to make it move downhill. To facilitate shaking, the troughs were suspended by chains and the reciprocating movement of short conveyors was applied by hand; the length of troughing that could be operated manually was limited and the use of a compressed-air cylinder with reciprocating piston soon followed. Suspension of conveyors at the coal face is often inconvenient, and the next step was the mounting of the troughs on rollers carried by roller tracks placed on the floor. The application of electric motors followed at a later date.

With the compressed-air drive the usual arrangement is that the piston pulls the troughing backwards uphill; on a level seam the roller path on the floor gives the required rise, troughing and coal then fall by gravity, until at the end of the stroke the motion of the trough is arrested and the coal slides forward.

In the electrically-driven shaker gear a crank is interposed and by the use of a system of links the uniform angular motion of the crank results in non-harmonic motion of a rocking arm. On one stroke of the rocking arm to which the conveyor is connected, the acceleration is nearly uniform during a considerable part of the stroke, and on the other stroke the acceleration rapidly rises to a high value. This special motion of the rocking arm, communicated by a connecting rod to the troughing, is used in conjunction with the appropriate form of roller path to propel the coal along the conveyor troughing.

On considerable inclinations a short harmonic stroke, with the troughs on straight upper and lower paths, is sufficient, but for conveying on the level and against gravity a number of interesting and somewhat complex problems are involved in adapting the rate of reciprocation, the length of stroke, the rate of acceleration, and the form of the upper and lower roller paths, all in combination, to the conditions of service and to the kind of coal (large or small, dry or damp) to be conveyed. It will be recognized that for imparting to the troughing a reciproacting motion at a rate between 60 and 90 strokes per minute the simple compressed-air cylinder, despite its comparative extravagance of power, has certain advantages over the electric drive with its rotary motor, reducing gear and crank.

The very wide range of conditions under which conveyors are applied, and the frequent necessity for adapting the conveyors to changes of seam conditions and mining circumstances, present abundant opportunities for exercise of ingenuity. The development of conveyor design and the improved capabilities and versatility of these machines are largely due to the initiative and resource of colliery officials in surmounting the difficulties with which the vicissitudes of mining confront them. These developments are reflected in the diversity of forms of shaking gears and their accessories produced by makers experienced in this speciality.

Conveyors may be described as semi-portable machines; the position of face conveyors is stationary throughout the working shift, but the whole length of the conveyor, and usually its driving gear, are moved towards the face once in each 24 hours; in thick seams or in hand-got seams the forward move may be every second day. Gate conveyors in respect of their delivering end may remain in position for months, but are gradually extended at the receiving ends as the face conveyors follow the face in its advance.

In operation, conveyors are not subjected to the same kind of treatment as coal-cutters, but face conveyors especially are similarly liable to excessively rough usage—usage that would soon wreck any plant not designed with special regard to the nature of the service.

When it is considered that 100 yards of medium-size conveyor trough when filled weigh about 6 tons, and of large trough about 10 tons, that nearly double that length is sometimes connected, and that this weight, supported on rollers from more or less correctly placed roller paths, must be reciprocated at a rate of between 60 and 90 double strokes, of between 2 and 10 inches, per minute, on one stroke the whole load being raised against gravity, it will be understood that the duty required of the shaking gear and of the whole trough structure is severe. But when it is further considered that the line of face may not be straight and that the troughs may be sawing into many wood props, that the floor may have considerable undulations, that accumulated dirt from the seam may prevent free movement of the troughing, that the roller tracks may become displaced, that soft floor or roof may allow the props that secure the shaking gear to become loose and the gear to depart from alignment, that irregular supply of trams at the loading position may require frequent stopping of the conveyor and the restarting of it with overloaded troughs, and that the complete stripping of the coal from the face to allow the coal-cutter to work on the next shift means that the conveyor must go on working at all costs, it will be realized that face conveyors of the shaking type have no ordinary task, and that anything that can go wrong with them will go wrong. Yet nothing must go wrong, for reliability and freedom from derangement of the conveyor is the essence of the economic success of mechanical conveying. The larger the daily output of the conveyor, the more important it is that there shall be no interruption to the regularity of output, and the greater is the responsibility of the conveyor.

The stresses to which such machines and their motors are liable have no relation to the useful work to be done, and, as in coal-cutters, factors of safety cannot be calculated. The machines must simply be strong enough, and the designs of the machines that are strong enough have been evolved by experience of the actual conditions of service.

Other Applications of Power at the Coal Face.

The drilling of rock or other strata too hard for cutting by the edge of a rotating drill is a special problem. The material must be attacked by percussive blows and the tool must reciprocate. The difficulties of applying electric power to this service are well known;

the compressed-air drill holds the field. The enormous economic importance of the rock drill applied to metalliferous mining, to quarrying, to tunnelling and to many other services besides coal-mining, has led to a probably greater degree of concentration of attention on the compressed-air rock drill than has been devoted by inventors to any other individual mechanical appliance. The result is that electricity has here a very highly developed competitor the convenience and effectiveness of which condone its admitted extravagance of power. The attempts to gain a footing with devices comprising combinations of electric motor, with springs or with compressed air or hydraulic links or relays, have not yet achieved technical and economic success, and so the nearest approach of the electric motor to rock-drilling near the coal face is the driving of an in-bye air compressor for air supply to percussive drills.

The drilling of shot holes for blasting in the coal face, and in the roof or floor strata to make height in the roadways or to provide material for packwalls to support the roof, is an important service which electricity directly applied to the tool has not yet succeeded in rendering; opportunity still awaits the successful designer. For drilling the coal by electric power a rotary drill with twisted stem to convey the cuttings from the hole is required. Attempts have been made to fulfil the conditions with electric drills, but none has succeeded in surviving the test of enduring service and in finding general acceptance by mining men. In such drills the principal desiderata are lightness and portability, adequate power, and robustness to withstand rough usage. The drills produced have conceded too much to lightness and have had inadequate power and strength, or they have had adequate power and strength at the expense of portability, and so, although at some collieries electric drills are used, shot holes in coal when not drilled by compressed air are still generally drilled by hand. In many electrically-equipped mines the advantages of compressed-air drills are obtained by the use of a portable air compressor driven by electric motor; the combination is mounted on flanged wheels to run on the mine track, and the output is usually equal to the supply of air to two drills for making shot holes in the coal and in the adjacent harder strata.

Other machinery that may be used at and near the coal face, not directly for coal production but for secondary services, such as motor-driven auxiliary fans, pumps and haulages, is too familiar to require detailed reference here.

Closely allied to the application of electric power at the coal face is the problem of improved lighting. At most modern collieries the pit bottoms are now not merely lighted by electric lamps—they are illuminated —and illumination pays because it facilitates activity and promotes safety in the operations conducted. Where the coal is hand-worked and the miners are distributed along thousands of yards of face, there is no economic alternative to the individual miner's lamp. But with intensive mining as now increasingly practised, whereby large outputs are got from comparatively short faces, new possibilities open out of general lighting at the face without reference to the individual workers. In recent years the standard of lighting in all surface industries has been greatly improved and it is now recognized that good lighting pays. On conveyor faces the men are grouped in considerable numbers, and although the work is not of a kind that demands a high standard of lighting, the light from the ordinary hand lamps is inadequate. The miner with his individual lamp which requires frequent attention that distracts him from his work, is a more or less isolated centre of activity, whereas with general lighting in the region of concentrated and intensive operations the men are brought into more effective association and the co-ordinating supervision is facilitated. In no surface work requiring grouping of men similar to that on conveyor faces would operations be carried on in such comparative darkness, and surface standards of lighting might with advantage be applied to conveyor faces. Improved lighting promotes activity in the sphere of operations and raises the efficiency of labour and so increases output. At the coal face it is conducive to safety, and where the seam contains dirt bands less dirt is sent with the coal to the surface. There can be no doubt as to the desirability of improved lighting at conveyor faces; the only question is that of feasibility. In open-lamp pits with a.c. power cables at the face, there is no difficulty; a small transformer stepping down to 25 volts is used, and flexible conductors with lamp sockets fitted at intervals of about 12 ft. are supported by the props along the line of face; the lamps—of 25 c.p. with frosted globes—are protected by suitable fittings. The work of Prof. W. M. Thornton has gone far towards making available, in closed-lamp pits, the advantages of coal-face illumination that have been demonstrated where the use of existing equipment is permissible.

Conclusion.

It must be accepted that electricity will continue to be excluded from the coal face in many collieries, but the number of these may be reduced by fuller knowledge by mining men of the characteristics of mining electrical appliances and of the conditions essential to securing and maintaining the highest degree of safety in their use, and by fuller knowledge by electrical men of the conditions of service of coal-face machinery and other in-bye electrical apparatus and of the rough nature of the treatment to which it is unavoidably subjected.

Practice of the intensive methods of mining, rendered possible by coal-face machinery, has a bearing on the permissibility of the in-bye use of electricity. The reduced pit room, the less surface of exposed gas-bearing coal, the diminished number, increased area, and improved maintenance of the air ways, and reduction of air leakages between intakes and returns, are all favourable to more effective ventilation, and therefore to safety in the use of electricity. On the other hand, the more rapid advance of the workings may in some gaseous seams liberate so much gas as to exclude electrical appliances at the face. This also applies to seams liable to the occurrence of sudden outbursts of gas, and to places in the working of normal seams where accumulation of gas may be difficult to avoid.

Where such ventilation can be provided that explo-

sive mixtures of gas and air are prevented, it is clear that electricity may be used with impunity. The measure of the risk that may attend the use of electricity is the degree to which the ventilation falls short, or may fall short, of the standard indicated above; in some seams that standard may be unattainable, in others attainable with difficulty. As already remarked, the mine manager, on whom the responsibility rests, has in every case the sole right to decide whether electricity shall or shall not be used. Generally, intensive mining by promoting effective and economical ventilation should, to the extent it does so, also promote the adoption of electrically-driven coal-face machinery.

The flame-proof enclosure of electrical apparatus is not designed for normal conditions of working, for the Regulations require that the men shall be withdrawn if the proportion of gas in the air reaches a figure which is much below the lower limit of danger of ignition. The purpose of flame-proof enclosure is to safeguard against any accidental or unexpected rise in the proportion of gas in the air, such as might be ignited by open sparks. A defect in design or maintenance that might destroy the flame-proof properties of an electric machine or appliance need not, and probably would not, affect normal working under normal conditions, and this renders the more necessary the periodic careful examination and maintenance of flame-proof apparatus. Assuming that apparatus is flame-proof when installed, the safeguard depends on maintenance of that state.

Everyone familiar with underground conditions knows the difficulty of securing adequate maintenance of underground electrical apparatus. It takes time to train the personnel, but experience is educating mining men in the necessity for due attention to this subject, and improvement is progressive. At large collieries with competent electrical staffs, adequate in number, very good standards of maintenance exist; only at such collieries is it wise to send underground delicate automatic devices which are only a snare if their condition and adjustments are not properly maintained.

Coal-mining has greatly profited by the versatility of the electrical engineer, and by the high standard of quality, both electrical and mechanical, of his products. In the main, the sphere of electricity underground will continue to be in the secondary services—ventilating, pumping, hauling and winding. In application to the primary processes of mining at and near the coal face, the use of electricity is restricted; although increasing confidence in electricity may lead to some relaxation, it is certain that compressed air, displaced by electricity from important services at and near the shaft and in intake airways, will be very much more difficult to dislodge from the region of the coal face.

There are wide differences between mining operations and the work carried on in factories and workshops; many of the underground conditions and the forces to be dealt with are beyond control of the mining engineer, and they govern his plans of operation. Yet the special difficulties and vicissitudes to which mining is subject are mostly amenable to a considerable degree of control by methods appropriate to the conditions. Intensive mining facilitates control of the physical conditions, and further, it facilitates control and increases the productive effect of labour. Intensive mining on the unit system implies a considerable amount of standardization of method, a daily cycle of operations at each unit of coal face is established, and several clearly defined operations are repeated in the same sequence day after day by men whose labour is specialized, and the work becomes comparable with some repetitive processes in workshops. These conditions render practicable the application to mining organization and operations, of the principles that in recent years have so greatly increased the productivity of labour in other industries—notably in engineering.

The services of the mechanical and electrical engineer to the mining industry have been manifold, but abundant opportunity remains and the measure of it is the high cost of coal production. The output per underground worker is too low, therefore too many men are in the industry—that is why wages are low and costs are high. By mechanical and electrical aids to production the output per man can be increased, wages and the status of the miner can be raised, and the cost and price of coal can be reduced.

[The discussion on this paper will be found on page 1015.]

THE DESIGN OF STORAGE-BATTERY LOCOMOTIVES FOR USE IN COAL MINES.

By L. MILLER, Associate Member.

(*Paper first received* 1*st January, and in final form* 12*th February,* 1926; *read before* THE INSTITUTION 8*th April,* 1926.)

SUMMARY.

This paper deals with the general considerations which affect the design of a battery locomotive for use in mines. The usefulness of such a piece of apparatus in a mine is briefly discussed and the general conditions to be met are described.

Detail points in the design are dealt with on broad lines, and the results are given of certain tests designed to compare the coefficient of adhesion obtained with specially prepared wheels and standard wheels on rails prepared to represent conditions met with in practice.

The various methods of obtaining flame-proof enclosure of the electrical apparatus are described.

Finally a rough idea of the cost of running a battery locomotive is given.

In order to design a battery locomotive which will be successful in operation it is necessary to study the conditions under which it will perform its work. It is therefore proposed, before dealing with the detail points in design, briefly to run over the general considerations bearing upon the question of the use of locomotives in mines.

GENERAL CONDITIONS.

The average cost of power in a mine works out at 1s. per ton of coal produced. It is clear, therefore, that any slight saving in power which might be achieved by the use of locomotives cannot have very much effect on the cost of the coal at the pit mouth. Any gain in output which may result from the more efficient gathering and conveying of the coal to the surface may, however, have quite a considerable effect on the price.

In considering the use of locomotives to replace rope-haulage systems, there is no doubt a very good case to be made out from the point of view of power-saving and efficient and speedy handling of the loaded trains, provided that the haulage roads are level. If gradients and faults exist, then the locomotive cannot compete with rope haulage from the point of view of speed, and, in fact, if the gradients are much worse than 1 in 20 the use of a locomotive may be quite impracticable.

For gathering work the locomotive cannot compete with a conveyor system from the point of view of speed. Conveyor systems can be used economically only in thick seams, and owing to the cost of the installation a case cannot be made out for thin or comparatively thin seams. In such cases the pit pony is used for gathering and marshalling the loaded tubs on the main haulage road and for keeping a supply of empty tubs at the coal face. This is a case where the battery locomotive can be used to replace the pit pony, with satisfactory results from the point of view of speed and cost and also from the purely humanitarian point of view.

The locomotive can also be efficiently employed for marshalling purposes at the junction of haulage roads.

DESIGN OF THE BATTERY LOCOMOTIVE FOR GATHERING PURPOSES.

From the foregoing it would seem that a case can be made out only for the use of the battery locomotive on thin seams. In such cases the gate roads will be very restricted in dimensions, and if the locomotive is to proceed by the gate road to the coal face it must be of such dimensions as to conform with the size of the gate road and to allow sufficient clearance to prevent fouling at curves.

The rails on these gate roads are usually put down in a very rough-and-ready manner, and the locomotive must be such that in the event of a derailment it can easily be placed on the rails again. The design, however, should be such that it is very difficult to derail the locomotive.

In addition, the design of the locomotive must be such that it can be taken down in the cage either in pieces or as a whole, run over the main haulage roads to the gate roads, and be able to clear all the obstructions which exist on the main haulage road.

In order to achieve these objects the following limitations are placed on the design :—

(1) The height, width and length of the locomotive are limited. These must conform with the dimensions which can be accommodated in the gate roads or the cage.

(2) The weight is limited to that which can be safely handled in the cage or in the case of a derailment.

(3) Ample clearance must be allowed underneath the locomotive to clear obstructions on the main haulage road, such as tub greasers, pulleys and other devices used for controlling the tubs.

(4) The locomotive must also be capable of giving sufficient adhesion to pull at least a load of 5 tons on a grade of 1 in 20 and have a speed on the level of about $3\frac{1}{2}$ miles per hour when pulling the same load.

(5) The wheel base of the locomotive must be such that the locomotive is capable of going round a curve of about 12 feet radius. The overhang when negotiating the curves must be such as not to foul the sides of the gate road.

(6) The whole of the electrical equipment must, of course, be flame-proof and of a type which it is safe to operate near the coal face. It must, in addition, be capable of being worked in the open air with rain falling and of being operated through a considerable depth of water without permanently affecting in any way the sanding gear or the electrical equipment.
(7) It must be possible to change the battery quickly.

In 1923 a Committee was formed, at the instigation of Mr. Markham, with the object of preparing a Specification covering the design of a battery locomotive for gathering service. Mr. Markham offered a prize of £1 000 for the best battery locomotive which would conform with certain tests. This Specification was prepared after very careful deliberation by the Committee and it outlines very successfully the general requirements of the battery locomotive as far as the above points are concerned. It is not proposed to duplicate the details contained in this Specification, but the information is available to anyone who is sufficiently interested in the matter.

Cost.—Obviously, where the locomotive is to compete with the pit pony, and its use can only be economically justified on narrow seams, the cost of the locomotive is of paramount importance. The locomotive must therefore be of the very simplest construction and the cost should be kept down to the lowest possible figure.

Standardization is, of course, the most satisfactory way of keeping down the cost, having got the simplest design, and it is only possible to reach the minimum cost on a locomotive which is being turned out in reasonable quantities and which does not vary in design.

Rail gauges and radius of turns.—The chief difficulty affecting standardization is the gauge question. The Markham Committee very wisely chose a 2-ft. gauge. It will be seen from the data contained in the recent B.E.S.A. Report on Colliery Light Rails,* which gives the results of an investigation on this subject, that out of a total of 468 collieries 132 are using the 2-ft. gauge. This Report also makes it clear that there are 56 different gauges in use.

With regard to the question of the minimum radius of the turns used, the Report also states that the average minimum radius of turn for secondary haulage work was found to be equal to from 3·5 to 4 times the gauge. This gives a figure slightly less than that in the Specification issued by the Committee.

Battery capacity.—The battery capacity given by the Committee was 12 kWh at the 1-hour rate, and not less than 18 kWh at the 5-hour rate of discharge. The working voltage was stated to be not more than 80. This, of course, fixes the maximum number of cells at 40, if 2-volt cells are used. In designing a battery, however, the largest possible individual cells that can be accommodated in the space available should be used. Obviously a battery composed of a few large cells would require less space than one made up of many small cells, because of the smaller proportion of tray and container to working material.

* C.A. (C.R.) 9295.

In addition, the cost and weight will be less for equal output. The cells will be stronger, there will be fewer to maintain and these will be more easily repaired.

These factors will all tend to keep the voltage below 80, rather than above it.

It is not proposed in this paper to go into the merits of the various cells which are now on the market, beyond just stating that although the nickel-iron cell is undoubtedly the most robust it has a very serious disadvantage in its high internal resistance, and this is especially inimical to its use where heavy gradients are in existence. Whatever battery is used, however, it must be capable of being short-circuited without injury and of being run down rapidly without serious detriment to its subsequent working. Arrangements should be made to see that the electrolyte cannot be spilled, and the cells should be of sufficient depth to ensure that there is no possibility of this occurring.

The life of a lead battery is about 3 years, and that of a nickel-iron battery is about double this, provided that reasonable care is taken of them and that they are kept clean, charged regularly and not left for long periods without charge.

Charging the batteries.—The question of charging has, of course, to be considered in connection with these batteries, but it does not in any way affect the voltage question. A motor-generator set will have to be supplied and the generator can be designed to give any suitable voltage. Automatic charging devices can be used with advantage, and they do away with any trouble due to overcharging. The frequency of the charge will depend upon the conditions. Usually it will be advisable to change the battery every shift, one battery being charged while the other is in service. Care should be taken to see that the water lost by evaporation during the charge is replaced, otherwise the life of the battery is impaired.

The nickel-iron battery will not sustain much damage due to carelessness in charging at too high a rate, but many of the lead batteries require careful treatment in this respect, and care must be taken with either type to see that the temperature does not rise above certain limits (110° F.) laid down by the manufacturers. A little reasonable care and a study of the instruction books issued by the manufacturers will do away with any charging difficulties.

Number of motors.—The choice lies between mounting a single motor which drives one axle, the second axle being connected by means of a connecting rod, or by a Cardan shaft and worm drive, and using two motors, one on each axle, connected through suitable gearing. The two-motor scheme has the advantage that by connecting the motor armatures and fields in series-parallel it is possible to do away entirely with resistances. This is, of course, impossible in the case of the single-motor drive, where resistances have to be used to reduce the speed. On straight runs any advantage due to this will not appear, but in marshalling the tubs and manœuvring, which will have to be done at a restricted speed, the advantage of the two-motor scheme will be apparent. This has been found to be the case in America, where the actual power consumption in

service has been found to be very much in favour of the two-motor arrangement.

Design of the motors.—The motors will, as far as the electrical design is concerned, be of the usual series-wound traction type. They will be totally enclosed and will consequently be subject to condensation due to the variable temperature under which they will operate. The insulation should therefore be of a type that will not suffer when subjected to such conditions.

It is very difficult to work out a schedule for a gathering locomotive, which is entirely different from a haulage service where the schedule can be determined and the R.M.S. current-rating of the motor worked out. The formula

$$\text{Horse-power} = \frac{583 \times \text{Weight in tons} \times \text{Miles per hour}}{\text{Efficiency of gears} \times 375}$$

gives a clue to the short-time rating of the motors. This gives a figure of 1·64 h.p. per ton per mile per hour. In obtaining this figure a coefficient of adhesion of 25 per cent is employed, plus 1 per cent for the locomotive friction. The efficiency of the gears is taken at 95 per cent. The 1-hour rating of the motors on locomotives employed for gathering service can usually be taken at roughly half this figure where the grades do not exceed 5 per cent and are not long.

Weight of the locomotive.—In order to provide the necessary adhesion the weight of the locomotive must be proportional to the grade on which the load has to be hauled. Usually an up-grade can be accomplished on the overload capacity of the motor, but the time required to surmount the grade should not exceed such overload capacity.

The usual formula for determining the weight is :—

$$\text{Wt. of locomotive in tons} = \frac{T(R_F + R_G + R_A)}{0{\cdot}25 \times 2\,240 - (R_G + R_A)}$$

where T = total weight in tons of trailing loads ;
R_F = frictional resistance of tubs, in lb. per ton ;
R_A = acceleration resistance, usually taken at 20 lb. per ton, giving an acceleration of roughly 0·2 mile per hour per sec. ; thus

$$\text{Force} = \text{Mass} \times \text{Acceleration} = \frac{0{\cdot}2 \times 5\,280 \times 2\,240}{3\,600 \times 32} = 20{\cdot}5 \text{ lb.}$$

R_G = grade resistance in lb. per ton ; this is 22·4 lb. per ton for every 1 per cent of grade.

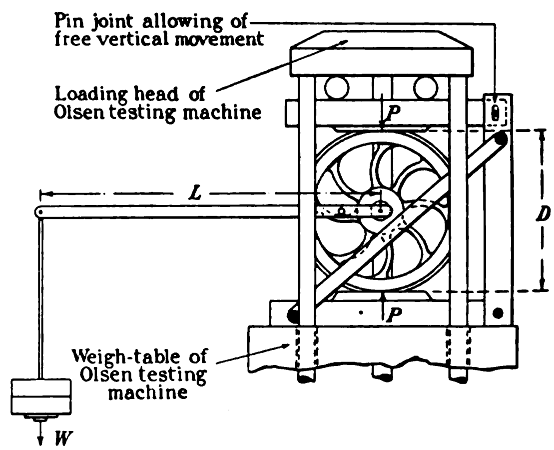
The figure of 0·25 for the coefficient of adhesion can as a rule be considerably improved at starting, and 0·3 is frequently used.

Coefficient of adhesion.—There are a great many things which affect the adhesion factor, and the author recently had some tests carried out on an 18-in. diam. steel wheel which show the effect of several variables on the coefficient of adhesion.

In an attempt to improve the adhesion the effect of inserting "Ferodo" into the wheel was tried. The wheel with "Ferodo" insertion was never used in practice, as the advantage was not considered to be sufficiently great and the life of the "Ferodo" insertion was regarded as doubtful. These figures are shown in the report of tests given in the Appendix. This experiment probably gives no new information and the results are included in order to show graphically how the conditions affect the coefficient of adhesion.

Attention is called to the effect of increasing the lines of contact from ½ in. to 1¼ in., which shows a marked improvement in the coefficient. This illustrates the importance, from the point of view of adhesion, of using flat-topped rails. The high figure obtained with sand with the ½ in. line of contact is due to some difference in the conditions not detectable by observation. This is indicated by the deep scoring which occurred when the wheel finally slipped. Increasing the diameter of the wheel also tends to increase the coefficient of adhesion.

It is quite clear from these tests that the sanding apparatus on the locomotive is of great importance in obtaining good adhesion, and the sanding gear should



Apparatus for determination of static friction of mining-type locomotive wheels.

be so designed that it cannot be put out of action when going through water.

Design of the controller.—The controller should be of very strong and robust design. The trend of development in controller design for heavy service is towards the contactor type. There are several reasons for this, the principal ones being :—

(1) This type of controller has been found in practice to stand up to severe conditions and maltreatment much better than the drum type.

(2) The renewal of the contacts becomes a very simple matter. The electrician can renew the whole of the contacts in a controller in a few minutes, using only a screwdriver. This cannot be accomplished with a drum controller, where the drum must invariably be extracted from the controller in order to fit new rings.

It is extremely inadvisable to rely on fuses for overload protection. Careless operation may result in the blowing of a fuse, and until the electrician has replaced it the locomotive will be inoperative.

The best arrangement is some form of interlocked circuit breaker which can be replaced only when the controller is in the "off" position. The controller

should be arranged with the so-called "dead man's" handle which, in the event of the operator releasing it, immediately cuts off current to the motors.

Braking.—Brakes should be supplied acting on all four wheels, and the design should be such that the pressure is equalized in each brake shoe. The shoes should be lined with "Ferodo" or similar friction lining to prevent any possibility of dangerous sparking.

The importance of sand as an aid to improving the adhesion, and consequently the braking effort, has already been emphasized.

It should be possible to apply the brakes by means of the foot as well as by hand, thus, in the case of emergency, leaving the operator with both hands free.

Type of drive.—There are at least three possible methods of gearing the motor to the driving axle:—

(1) Double-reduction chain drive using some form of silent chain for the first reduction, and an ordinary roller chain for the low-speed drive. The high-speed drive should be enclosed and, preferably, the low-speed drive as well.
(2) Double- or single-reduction spur-gear drive. This also should be of the enclosed type.
(3) Enclosed worm drive.

In America the tendency is to adopt either spur or worm gearing, and the chain drive is not regarded as sufficiently robust for the service. This is what would be expected for American conditions, where a great many large trolley locomotives are in service engaged on straight haulage work and operating at speeds up to 10 miles per hour at their rated draw-bar pull. For the small powers and low speeds required for gathering service the author believes that a properly designed chain drive will give satisfactory service. It is cheap and easily renewed at low cost, and can be accommodated in a small space without sacrificing the necessary clearance required to avoid the obstructions in the haulage roads.

Ball or roller bearings.—The saving in power due to the use of roller bearings in the tubs and locomotive axles will amount to 40 per cent of the power required to overcome friction.

The use of ball bearings on the motor will result in a reduction in the length between bearings and will assist in obtaining a satisfactory flame-proof design.

The actual saving in power consumption, taking into account braking, flange and air friction, grades and curves, will probably amount to as much as 20 per cent. This saving will enable a smaller battery capacity to be utilized for the same amount of work. The extra capital cost entailed in fitting roller bearings to the tubs and locomotive axles should soon be wiped off.

Roller bearings are, however, not likely to be received with any enthusiasm by the colliery personnel.

Winches.—It has been suggested that where the gate roads are such as to have a heavy grade against the loaded tubs, or where they are of such dimensions as to make it difficult for the locomotive to proceed to the coal face, a winch driven from the propelling motor would be an advantage. This would enable the full rated power of the motors to be utilized without considering the question of adhesion, and the loaded tubs could be hauled up a grade on which the locomotive could not operate. In fact the locomotive would, in addition to its marshalling duties, act as a portable haulage. By arranging a sheave on the roof timbers it could be utilized when erecting or dismantling pumps, coal-cutters, erecting or withdrawing props, etc.

There are, however, difficulties in the way of designing a gathering locomotive with a winch attachment. These are chiefly concerned with the limitation in dimensions, and the design of a satisfactory clutch member to declutch from the wheels and clutch on to the winch when required. These difficulties, so far as the author is aware, have not been quite satisfactorily overcome.

Flame-proof enclosure of the electrical gear.—The enclosure of all electrical apparatus used on the locomotive must conform with the definition laid down in British Standard Specification No. 229 and must be capable of withstanding the tests laid down in that Specification. The definition is as follows:—

> "A flame-proof enclosure (including explosion-proof) for electrical apparatus is one which will withstand without injury any explosion that may occur in practice within it under the conditions of operation within the rating of the apparatus enclosed by it (and recognized overloads if any associated therewith) and will prevent the transmission of flame such as will ignite any inflammable mixture which may be present in the surrounding atmosphere."

The problem of providing suitable protection therefore resolves itself into providing a means which will give sufficient relief to prevent the pressure increasing to a dangerous value, having regard to the strength of the enclosure, and at the same time will prevent flame reaching the outside atmosphere at such a temperature as to ignite it.

The "Safety in Mines Research Board" have issued a report on "Flameproof Electrical Apparatus for Use in Coal Mines" by Messrs. Statham and Wheeler which deals thoroughly with the question of "Flange protection." This is described by them as follows:—

> "Flange Protection.—Release of the pressure produced by an internal explosion is provided at flanged joints, the spacing between the flanges and their width being so proportioned that flame cannot reach the outer atmosphere."

This document deals very fully with the question of flange protection and demonstrates without any doubt whatever that this simple method of protection is most effective.

Although Messrs. Statham and Wheeler have not dealt with the alternative methods of protection, the matter has been dealt with by the American Bureau of Mines and several Continental investigators.

The alternative methods in question are:—

(*a*) Gauze or perforated plate protection and various combinations of the two.
(*b*) Gauze protection with the addition of a spring-controlled relief valve.
(*c*) Tubular or labyrinth protection providing a long, tortuous path for the passage of flame.

(*d*) Plate protection consisting of a large number of thin plates with distance-pieces between them, the flame being passed between the plates.

It is significant that 15 years ago manufacturers were experimenting with devices of this kind, but nowadays none of these are being used by the people concerned in these experiments. They have practically all adopted flange protection.

There are many reasons for this; for instance, gauze is not sufficiently mechanical to stand up to everyday wear and tear, especially in a mine, and even if protected by a valve there is grave danger of the valve being damaged so that it cannot operate. It must be remembered that devices of this kind are fortunately not often in operation and, in fact, may never be called upon to operate, and it is the danger of carelessness due to long immunity which has to be guarded against.

Apart from the question of mechanical damage or incorrect assembly, there is the proved fact that gauze or labyrinth protection very often gives too free a passage for the escape of pressure, with the result that the pressure in the enclosure actually falls below that of the outside atmosphere. This difference in pressure results in a fresh explosive mixture being immediately drawn into the enclosure. This may cause another explosion to take place, and this may go on until ignition actually occurs. Protecting the gauze by a valve might be expected to do away with this difficulty. It is, however, a very difficult thing to devise a valve which would be reliable under the conditions of operation.

Labyrinth or tube protection may suffer from the same defect as gauze. There is no doubt, however, that successful protection can be designed on these lines so long as care is taken to ensure that the path is not too wide, is properly protected, and cannot be wrongly assembled.

Plate protection is also perfectly safe, providing the plates can in turn be protected. The arrangement, however, can easily be assembled incorrectly and is so fragile that it has generally been left out of consideration.

The protective device should have the following features :—

(1) It should be capable of absorbing a large amount of heat.

(2) It should afford as much relief to the pressure as is consistent with the prevention of the flame igniting the inflammable mixture outsider the enclosure.

(3) It should be of a very robust nature and so constructed that it cannot be assembled incorrectly.

It is the author's opinion that flange protection most fully meets this specification, and the designer has complete information on this subject in Messrs. Statham and Wheeler's report previously mentioned.

The battery box must also be made strong enough to withstand a fall of roof or similar accident without crumpling, and should prevent damage to the cells or a short-circuit in the event of such an occurrence. Hydrogen may be evolved when the battery is being charged, so that the ventilation provided for the battery box should be ample to allow this gas to escape and not imprison it so that it is present when the locomotive is in service. If the battery box is subdivided in order to reduce the weight of an individual part or to obtain additional strength, then the connections between compartments must be made through flame-proof bushings and care must be taken to prevent intercommunication between compartments which may cause, in the event of an explosion in one, a rise of pressure in the next.

The plug and socket or jumper which is attched to the battery box must be so designed that it can be locked in place and cannot be pulled out except by an authorized person. The design should be such that, in the event of a short-circuit in the plug, flame cannot be communicated to the atmosphere. The controller

TABLE 1.

Medium	Load in tons	Static coefficient of friction	Average coefficient	Remarks
Steel wheel on rust and pitted steel rail.				
Dry	¾	0·323	0·323	As the rail became polished the friction coefficient became smaller.
Steel wheel on rough filed steel rail; rust pits NOT *entirely obliterated.*				
Dry	¾	0·331	0·331	This condition could not be maintained.
"Ferodo" wheel on rust and pitted steel rail.				
Dry	¾	0·389	0·389	Remarks as for steel wheel.
"Ferodo" wheel on rough filed steel rail; rust pits NOT *entirely obliterated.*				
Dry	¾	0·352	0·352	Remarks as for steel wheel.
"Ferodo" wheel on smooth steel rail greased with paraffin wax.				
Paraffin wax ..	½ ¾ 1	0·0896 0·101 0·117	0·102	These tests were made to determine the effect of a lubricant having great viscosity.

cover and all doors easily accessible should be locked so as to prevent unauthorized persons tampering with them. The terminal boxes of all the apparatus used must, of course, be made flame-tight, and where the cables are taken off they must be provided with suitably designed flame-tight bushes.

Cost of running.—No data are available, so far as the author is aware, as to the running costs of locomotives as compared with ponies on gathering service in this country.

In America the conditions are so different that data from this source do not seem to be applicable. The *Coal Age* of the 16th February, 1922, an American publication, contains some interesting data, which, although the figures are not applicable to the conditions in England, nevertheless show the trend of opinion in America and the results achieved by the use of battery locomotives.

A gathering locomotive will cost £400 to £500 per annum to run, and it will be necessary to replace at least three ponies to cover this expense. It is claimed in one of the cases mentioned in the above issue of The *Coal Age* that one locomotive replaced six mules. Where the conditions are such in this country that it is possible for the locomotive to replace six pit ponies the case, in the opinion of the author, is very strongly in favour of the battery locomotive, from the point of view of running cost and speed of handling the coal. The conditions vary to such an extent in every mine that it is impossible to lay down any hard-and-fast rule.

TABLE 2.

Medium	Load in tons	Static coefficient of friction	Average coefficient	Remarks
Steel wheel on rough filed steel rail (line of contact ½ in. at most).				
Dry	¼	0·202	0·205	Owing to deep scoring, the rail was rough filed and the wheel smoothed after each test.
	½	0·204		
	¾	0·200		
	1	0·213		
Water	¼	0·174	0·182	Care was taken to ensure that the surfaces were free from oil and were thoroughly wetted. The rail was maintained in the rough filed condition.
	½	0·19		
	¾	0·18		
	1	0·184		
Oil and water ..	¼	0·167	0·174	The water appeared to have no effect on the result and merely lay on the oily surface in globules.
	½	0·167		
	¾	0·176		
	1	0·187		
Sand	¼	0·453	0·472	Deep scoring occurred with all loads.
	½	0·431		
	¾	0·502		
	1	0·504		
"Ferodo" wheel on rough filed steel rail (line of contact ½ in. approx.).				
Dry	¼	0·248	0·252	It was necessary to file the surface after each test. From the appearance of the "Ferodo" it played an important part in the adhesion.
	½	0·276		
	¾	0·23		
	1	0·254		
Water	¼	0·218	0·196	Remarks as for steel wheel.
	½	0·20		
	¾	0·184		
	1	0·186		
Oil and water ..	¼	0·13	0·129	Remarks as for steel wheel.
	½	0·135		
	¾	0·13		
	1	0·12		
Sand	¼	0·57	0·551	The "Ferodo" and steel were both scored at all loads. The "Ferodo" appeared to suffer most.
	½	0·52		
	¾	0·553		
	1	0·56		

REPORT OF TESTS ON THE 18-IN. DIAMETER MINING LOCOMOTIVE WHEELS TO ASCERTAIN THE COEFFICIENT OF ADHESION.

General.—The tests were made on two wheels :—

A plain cast-steel wheel.

A cast-steel wheel with "Ferodo" insertion. The "Ferodo" was inserted in a spiral groove cut in the face of the wheel.

The coefficient of adhesion was obtained with both wheels in a perfectly clean and smooth condition and the rails in the following conditions:—(1) Extremely rusty; (2) reasonably clean, as would be expected in normal service; (3) perfectly smooth and bright.

In addition to these tests, the effect of a very heavy grease on the rails was ascertained by using paraffin wax. Paraffin wax was used in this case in preference to axle grease as being less likely to break down under heavy loads, and to represent more closely the conditions which might arise with a mixture of axle grease and fine coal dust.

(1) *Rails in extremely rusty condition.*—As this was regarded as a condition not likely to be, or at any rate very infrequently, met with under normal working conditions, only one set of figures was obtained, and these were with the rail in a perfectly dry condition.

(2) *Rails in reasonably clean condition.*—With the rail in this state, figures were obtained for the coefficient of adhesion with the rail treated in the following manner:—(*a*) Perfectly dry; (*b*) sprayed with water; (*c*) sprayed with water and oil; (*d*) dry and sandy.

TABLE 3.

Medium	Load in tons	Static coefficient of friction	Average coefficient	Remarks
Steel wheel on smooth steel rail (line of contact 1¼ in. approx.).				
Dry	¼	0·224	0·24	After each test the wheel and rail surfaces were touched up with a smooth file, washed with methylated spirit and dried.
	½	0·246		
	¾	0·244		
	1	0·245		
Water	¼	0·249	0·25	The surfaces were examined after each test and, when necessary, due to scoring, were filed smooth.
	½	0·248		
	¾	0·252		
	1	0·253		
Oil and water ..	¼	0·237	0·251	During this series of tests the surfaces, of both the wheel and rail, remained in perfect condition and touching up was not necessary. Apparently the oil film completely broke down for the higher loads.
	½	0·254		
	¾	0·253		
	1	0·260		
Sand	¼	0·264	0·301	The appearance of the surfaces remained constant throughout the tests and they were consequently not interfered with. For any given load the results were fairly consistent.
	½	0·327		
	¾	0·30		
	1	0·313		
"Ferodo" wheel on smooth steel rail (line of contact 1¾ in. approx.).				
Dry	¼	0·250	0·261	The surfaces were carefully polished and dried between each test.
	½	0·281		
	¾	0·259		
	1	0·254		
Water	¼	0·286	0·276	At intervals a return was made to the dry condition in order to verify that the increased static friction with the wet surfaces was a normal effect; this was found to be the case.
	½	0·272		
	¾	0·266		
	1	0·279		
Oil and water ..	¼	0·185	0·213	The effect of oily surface is most marked with the smaller loads—thus bearing out the explanation given for the steel wheel, i.e. that the oil film breaks down under load.
	½	0·203		
	¾	0·223		
	1	0·240		
Sand	¼	0·394	0·431	The grains of sand became deeply embedded into the "Ferodo," thus altering the nature of the surface in contact.
	½	0·45		
	¾	0·45		
	1	—		

(3) *Rails in perfectly smooth and bright condition.*—With the rails in this state the same tests were carried out as in (2).

Apparatus.—The arrangement of the apparatus is shown in the figure on page 1006.

Results of tests.—The results of these tests are given in Tables 1, 2 and 3.

[The discussion on this paper will be found on page 1015.]

ELECTRICITY IN MINES: A SHORT SURVEY.

By R. NELSON, Member.

(*Paper received* 1*st January, and read before* THE INSTITUTION 8*th April*, 1926.)

SUMMARY.

The paper provides a general review of the present position of electricity in mines, with particular reference to coal mines. Dealing with the safety aspect, it is claimed that the special requirements of colliery work have been amply met by manufacturers of electrical apparatus. It is further claimed that Great Britain has established a lead over other countries in respect of the design of mining electric plant. The question of public versus private supply is discussed, and the author states that, in his opinion, supply from an outside source is overwhelmingly the correct policy wherever two rival estimates show an equal, or nearly equal, financial result.

Some general statistics are given and the conclusion is ultimately drawn that one-half the motive power of the mines of Great Britain still remains non-electric.

Finally, some important directions in which the use of electricity in mines is likely to increase are mentioned.

The Annual Report with statistical appendices issued by the Secretary for Mines forms a very good indication of the extent and importance of the mining industry. The statistics show, by the number of persons employed and the value of the output, that in Great Britain coal mining is of much greater importance than metal mining.

This survey will be mainly concerned with the use of electricity in coal mines.

The general position of electrical engineering in relation to mining is worth a few moments' consideration. Mining was already an old industry with fixed traditions and well-established practices long before electricity made its appearance. In order to obtain due consideration, electrical engineers had therefore to overcome the natural tendency to follow old and well-tried methods, as against the adoption of a new, untried, and even "mysterious" agent. It is chiefly for this reason that although the special adaptability of electricity for use in connection with mining was mentioned in a paper before the Institution of Mechanical Engineers as early as the year 1852, it was not until 1883 that the first electric motor was set to work below ground in a British mine. This was at the Trafalgar Colliery, Drybrook, Gloucestershire, and the person responsible was the late Sir Francis Brain. Electrical and mining engineers had, however, still to do a good deal by way of educating each other, and themselves, before they evolved practical and satisfactory solutions of all the problems presented by the distribution and use of electricity under mining conditions. There is now more than 1½ million horse-power of electric motors in use in and about the mines of Great Britain, whilst it is doubtful whether there was as much as 10 000 horse-power in 1900. This indicates a greatly accelerated rate of growth during recent years, but, as will be seen later, the total is, in itself, a moderate one, having regard to the field for the further use of electricity that still exists on the surface and below-ground in mines.

The increased rate of growth just mentioned dates from the introduction of the three-phase induction motor and has been due partly to its convenience and reliability, and partly to increased confidence in the safety of electricity. In spite of the great improvements which have been made in distribution apparatus, and the high efficiency and low first-cost of modern electric motors, there is, however, still some inertia to be overcome in the coal-mining industry (which has always, and quite rightly, examined every new process with deliberation) before full advantage can result to that industry from the present situation. Whatever demerits electricity may possess, it can at least be claimed for it that it is practically and economically far and away the best medium at present known for distributing power over long distances below ground. It is proposed now to glance at the present position of electricity in mines and afterwards to outline the directions in which we may expect to see the uses of electricity further developed.

It will be convenient to deal first with one general aspect of the matter, namely, the use of electricity in mines from a safety standpoint. On this subject it is possible to quote some very important evidence by two well-known mining engineers. Prof. Douglas Hay and Mr. I. C. F. Statham recently gave an interesting account of some investigations carried out by them in the Mining Department of the University of Sheffield into the design of flame-proof casings for electrical apparatus.* All kinds of apparatus were submitted for test—motors, controllers, switches, coal-cutters, gate-end boxes, and cable joint-boxes—and in the end Prof. Hay and Mr. Statham reported as follows:—

> "It is satisfactory to be able to record that very few failures occurred under test; in fact, with one exception, such failures as there were took place under abnormal conditions imposed to determine the limits of safety, so that failure was anticipated."

Prof. Hay and Mr. Statham sum up their view of the risk to be apprehended from the use of well-chosen electrical mining apparatus in these words:—

> "With the continued improvement in the standard of design and maintenance of electrical plant, it is obvious that in the future the risk of danger arising from the use of electricity will be almost negligible.

* DOUGLAS HAY and I. C. F. STATHAM: "Flame-proof Design of Casings for Electrical Apparatus: An account of Investigations carried out in the Mining Department of the University of Sheffield," *Transactions of the Institution of Mining Engineers*, 1923-24, vol. 67, p. 23.

Side by side with this advance there is also the steady improvement in the standard of ventilation in mines and a progressive diminution in risk from the presence of coal dust. It must be believed that the risk of failure of apparatus coinciding with the presence of dangerous conditions due to firedamp and coal dust will be remote, and this fact must tend towards an increasing use of electricity underground."

The author agrees with them. The electrical manufacturers of Great Britain have amply proved their willingness and ability to meet the special requirements of coal mining, so that, given the correct choice of apparatus and due care and attention to its maintenance, a high degree of safety is now readily within reach. The present satisfactory position was, however, not reached without effort. Gloomy fears and predictions of disaster were frequent between 10 and 15 years ago, when "electricity in coal mines" passed through a critical period. To meet this situation a sustained and eventually successful effort was made by British electrical manufacturers to establish electricity in the confidence of the mining community. One good result has followed. The author's own experience is that British-made mining electrical apparatus is at the present moment substantially better than German-made apparatus. In fact, in this connection it may reasonably be claimed that we have established a lead over *all* other countries.

It would be possible at this point to leave the safety aspect, but the author wishes to add that the correct solution of safety problems in mining owes a great deal to the skill and perseverance of Prof. W. M. Thornton, who gave a detailed account of his work, extending over a period of 15 years, in a recent paper before the Institution.*

The first general question which arises in connection with the use of electricity in mines is the source from which the current is to be derived. Supply from an outside source, whether from a public supply or from a neighbouring privately-owned generating plant, has not, everywhere, commended itself to colliery owners. This is one of the points about which there still remains a very common difference of opinion between electrical and mining engineers. In their Memorandum of Evidence before the recent Royal Commission on the Coal Industry, it is given as the considered view of the Council of the Institution of Mining Engineers that "unless power companies can supply current at prices very largely below those now in operation the major proportion of the collieries are correct in continuing to produce their own power, either from exhaust steam or by waste heat from other sources or by generating plant using low cost fuel."† It will be observed that the statement is not made in respect of a few examples of large colliery establishments. If it were, something might be said for it. It is made in respect of the "major proportion of the collieries," and implies support of the policy of continuing to use private generating plant for colliery purposes, even where supplies of reasonable efficiency are available from outside sources, unless, indeed, such supplies can be obtained "at prices very largely below those now in operation." The question raised is one the solution of which requires no special mining or electrical knowledge, and it is therefore one about which difference of opinion must be based either upon difference of outlook, or upon failure to appreciate on one side or the other, or on both sides, the full merits of the case from the opposite point of view. It is probable that each of these factors has contributed in most cases where differences of opinion have arisen.

A mining engineer justifying the existence of a private generating plant such as is seen "at the major proportion of the collieries," has usually the argument of a plant-in-being to support his view, coupled with the utilization of fuel a sale for which cannot always, or readily, be found. In some cases waste heat from one source or another may be available. On the other hand, to set against these substantial arguments he has very rarely a complete appreciation of the fact that his power plant, as such, regarded from the point of view of efficiency, is a very indifferent performer indeed. Further, unless he is an exceptional man, his method of keeping power costs may well leave something to be desired in respect of accuracy and completeness, and it is only where accurate records are available that a true comparison of costs can be made. As the result of investigation at a colliery it often transpires that the prevailing idea of the cost per unit of current has its justification more firmly founded on tradition than on measurement. The official figure upon which argument is conducted is often based upon an engine or turbine test under full load, remote in point of time, with a definite steam pressure, dry steam, tight valves, and a sustained vacuum; conditions which the engine or turbine may never have the good fortune to encounter again in the long course of its useful career. It is, at any rate, unusual for a careful record to be kept of the output of the generators on the one hand, or of the amount of fuel burnt in the boiler furnaces and the cost of upkeep and repairs on the other, to say nothing of provision for depreciation, and it is only where such records are kept, and due provision is made, that it is possible for any approach to a close comparison of costs to be made.

An electrical engineer, an emissary of the power company, subjecting a plant such as is above described to friendly scrutiny, concludes at once that from the point of view of efficient power generation he is contemplating an anachronism. He has been taught to believe that the important requirements of a source of power for any industry are reliability, flexibility, and efficiency, and it is most likely that he will regard all three of these first principles as grossly outraged by the plant before him. He further reflects that power-plant equipment is inherently expensive, and he is amazed that it should be considered economically possible to continue to sink capital, bearing interest and depreciation charges of not less than 15 per cent per annum, in power equipment, when there exists the alternative of carrying the whole (or a large proportion) of the cost of power as a working expense, without involving the expenditure of any large capital sum. How flourishing must be the condition of an industry

* W. M. THORNTON: "Researches on the Safe Use of Electricity in Coal Mines," *Journal I.E.E.*, 1924, vol. 62, p. 481.

† *Transactions of the Institution of Mining Engineers*, 1925-26, vol. 70, p. 119.

to which power is a prime necessity and which can afford to pay so little attention to its efficient generation! But the electrical engineer may in his turn harbour some hallucinations. He sometimes fails to appreciate that a saving of even 50 per cent in the cost of power may mean no more than an improvement of 5 or 6 per cent in the pit-head cost of the coal won. He may also overlook the fact that it is the exception rather than the rule for colliery directorates to build up a reserve for the purpose of meeting the cost of modernizing the colliery equipment from time to time, and that lack of funds is therefore sometimes the final and compelling reason for continuing obsolete plant in use for long years after it has served its time and generation. For these reasons many colliery undertakings hesitate long before deciding to use current from an outside source.

The following is, in the author's view, the conclusion of this matter. In many cases the point at issue is regarded too narrowly. It is often determined mainly or solely by a comparison of actual or estimated generating costs with the cost at which power can be purchased, leaving more or less completely out of account the advantages, many of them considerable, which go with the purchase of current from an outside source. Assuming a fairly close degree of correspondence between the rival sets of figures, the question goes some way towards answering itself if its implications are thoroughly appreciated.

The practical advantages which follow from the purchase of current from an outside source are very important. Amongst them are: (1) The ease and quickness with which new machinery can be introduced without the necessity of additional capital outlay on generating plant; (2) the greater reliability, in general, of the supply, because it is the exception rather than the rule to see adequate spare plant provided at a colliery; (3) the convenience of having current "on tap," so that power and light are available at all hours of the day and night, at week-ends and on holidays, without the necessity of employing at these odd times more than the minimum of labour, and (4) the saving of time, money and worry, arising from the fact that the hitherto constantly recurring power problem has been, once and for all, definitely and finally settled. It is of course very difficult to give each of these facilities a cash value, but each of them definitely assists production by enabling the management to reduce idle time, one of the important factors tending towards the present-day diminution of output per employee in British coal mines. The matter of output per employee touches at once upon the most important result which usually follows from an unlimited supply of power, namely the increased *use* of mechanical power. It is only by this means that the output per employee can be increased and the cost of coal lowered without affecting the daily wages of the workers.

There is one other point. The adoption of electricity for winding purposes without heavy first cost, already possible in two or three of the coal-fields, is gradually being made possible elsewhere by the largely increased size of the units of generating plant now being installed in the stations of public supply authorities. Partial electrification of a colliery, leaving out the winding engines and the larger steam engines such as the fan engine, involving only partial shutting down of the colliery boiler plant, sometimes gives a somewhat disappointing result. Many schemes which have been only moderately successful as partial electrifications, have been greatly improved by a complete change-over. The winding engines are usually the last item to be converted, and they are, of course, the largest steam users and the most wasteful of all colliery steam engines.*

For these reasons the author is of opinion that the future will show a growing tendency towards the purchase of power from an outside source. In support of this conclusion it may be pointed out that in the newly developed South Yorkshire and Nottinghamshire coal-fields the larger collieries are gradually being interconnected by a system of transmission mains, so as to cheapen the cost of power by enabling most of the power plants to be shut down at week-ends and on holidays and by utilizing more completely the available reserves of surplus power and spare plant. The collieries are beginning to appreciate that there is, after all, some merit in co-operative working. That is a short step, but a definite one, in the right direction.

The relative importance of the coal-mining and metal-mining industries, and the extent to which electricity is at present being utilized in mines, may be gauged by the information given below, which has been abstracted from Mines Department records:

Coal mines.—The total amount of coal raised in Great Britain in 1924 was 267 061 027 tons, and the number of persons employed 1 213 724.

The total number of coal mines at work in 1924 was 2 855, of which 1 629 were wholly or partly electrically equipped. It follows that 1 226 mines, probably most of them small mines, were still at the end of 1924 without any electrical equipment.

The horse-power of motors installed in and about coal mines at the end of 1924 is given below:

Surface	671 036 h.p.
Underground	810 896 h.p.
Total	1 481 932 h.p.

An analysis of the motive power employed above and below ground shows the following:—

	h.p.
Winding	107 139
Haulage	411 816
Pumping	348 803
Ventilation	102 911
Coal cleaning..	112 660
Coal cutting	92 121
Miscellaneous uses	306 482
Total	1 481 932

* In the December (1925) number of *World Power* there is an interesting statement by Mr. J. F. Perry on the subject of the efficiency of power production at collieries. He says: "It is very clear that even if the efficiency of the power plant is substantially increased it would have little, if any, effect on the present crisis, which only a difference of several shillings per ton can effect." Mr. Perry is of course quite correct, and what he adds later must be read with the general conclusion just mentioned in mind. He goes on to estimate that if the whole of the collieries were electrified the annual consumption of energy would be 4 430 million units, and the annual coal consumption for colliery purposes 3 950 000 tons. The actual coal consumption in 1924 was approximately 16 000 000 tons. A possible saving of 75 per cent of the coal used for colliery purposes is indicated, and even though it is quite clear that Mr. Perry has in mind some approach to a counsel of perfection, the result of his calculation is still very striking.

Taken over the last 10 years the average rate of increase per annum of the horse-power of electric motors installed below ground has been 6·83 per cent. The actual percentage increase of the total horse-power of motors installed below ground at the end of 1924 over the total horse-power installed below ground at the end of 1915 is 73 per cent.

Metalliferous mines.—With reference to the amount of metalliferous ore raised in Great Britain in 1924, the following are the principal items: Iron ore 11 050 589 tons; lead ore 14 294 tons; tin ore 3 546 tons; manganese ore 2 457 tons; zinc ore 2 317 tons. The number of persons employed in metal mining was 19 481.

The total horse-power of motors installed in and about metalliferous mines at the end of 1924 was 23 524. Of this total, 11 753 h.p. is installed on the surface and 11 761 h.p. underground. The chief uses are for pumping (9 391 h.p.) and ore-dressing (2 806 h.p.). The Mines Department records show that the horse-power of electric motors installed above and below ground in metal mines has increased by 17 per cent in 5 years.

The statistics above quoted do not of course give any indication whatever of the total amount of power of all kinds installed in and about the mines, and there is no definite information available from which an up-to-date estimate can be made. The last census of production of the United Kingdom published in 1912 refers to data collected during the year 1907. It was then estimated that the total horse-power of engines in mines and quarries amounted to 2 495 134. It is certain that the horse-power utilized in quarries is comparatively small, and it is, the author thinks, fair to assume that the power utilized in coal mines cannot now be much, if any, less than 3 million h.p. If that total is anywhere near to being correct, it follows from data already given that about one-half the engine capacity in the mines of Great Britain still remains non-electric.

The increase of electrical horse-power in each year is made up of (*a*) conversions from other forms of motive power and (*b*) additional motors. It is probable that the newly installed horse-power due to the former still greatly exceeds the newly installed horse-power due to the latter, and important conversions will continue to be made, for there are coal mines which continue to distribute compressed air from the surface, and more which remain reluctant to carry current beyond the shaft bottom. These decisions may be wise in a few cases, but it is difficult to believe that they are justified in every case that exists.

The above is the main direction in which electrical engineers may look for further extension in the use of electricity in mines. Other important directions are (1) the greater use of inbye machinery in place of hand-putting and pit ponies, (2) the extended use of coal-face machinery, and (3) the extended use of electric safety lamps.

As to (1), the number of pit ponies is steadily, if slowly, decreasing, but in 1924 there were still more that 65 000 employed below ground in British mines. It is reasonable to expect, and to hope for, an accelerated rate of decrease in this number and the gradual establishment of a complete system of mechanical haulage, wherever possible, from the coal face to the shaft.

With regard to (2), there are few places where the increased use of machinery is more desirable than at the working face. The coal-face worker's task is the most severe, and statistics show it to be the most dangerous, of all underground occupations; he therefore needs all the relief that improved conditions of working and efficient mechanical appliances can offer. On the other hand, it may be pointed out that the growth in the use of coal-cutting and coal-conveying machinery in British mines from year to year is disappointingly small. The question involved is one upon which it would be rather out of place for an electrical engineer to hold too decided an opinion, but with less than 20 per cent of the coal output machine-cut, it may reasonably be asked whether an accelerated rate of increase in the number of coal-cutting machines employed, if practicable, would not be one unobjectionable method of increasing the output per employee, the gradual shrinkage of which in most of the coal-fields is one of the present difficulties of the coal-mining industry.

On the subject of (3), no survey would be complete without reference to the continuous and rapid progress which has been made during the last 10 or 15 years in the use of electric safety lamps. In the year 1912 there were only 10 727 electric lamps in use, but progress is best indicated by a short table compiled from the Mines Department records:

Year	Number of electric lamps in use	Number of oil safety lamps in use
1912	10 727	697 664
1916	126 784	610 821
1920	245 900	635 127
1924	356 817	576 318

Miners' electric lamps as now used give not less than 1 candle-power at the end of 9 hours' use. They are fitted into a 2-volt acid or a 2·5-volt alkaline battery, and weigh about 6 lb. More light can of course be obtained, but only at the expense of added bulk and weight, and it has always been a debatable point whether the advantage of additional light is worth the handicap of added weight. Larger and heavier lamps giving more light are, however, beginning to come into use for hewers and others able to hang up their lamps while they are at work. It is unlikely that the electric hand-lamp will displace the oil safety-lamp entirely, but it seems clear that the number of electric lamps will soon exceed the number of oil lamps in use.

In conclusion the author would refer briefly to two further directions in which electrical enterprise and research may hope to be of added assistance. The first is the prospect held out by Prof. W. M. Thornton's experiments of a great improvement in the matter of underground illumination from the ordinary power distribution system, with due and proper regard to all the requirements of safety. The details were explained

by Prof. Thornton in his paper of which mention has already been made. The second has reference to storage-battery locomotives for underground use. This development may well prove to be a very important contribution towards the solution of the pit-pony problem. Electrical engineering is in fact building up the reputation of an ever-ready help to the mining industry. The steam engine in its early days was often referred to as "the right arm of mining operations." It may not unreasonably be claimed that the position once held by the steam engine is now, in 1926, firmly occupied by electricity.

Discussion before the Institution, 8 April, 1926, on the Three Papers by Mr. S. Mavor, Mr. L. Miller and Mr. R. Nelson, Respectively.

Mr. J. A. B. Horsley: Mr. Mavor refers to the priceless advantage possessed by electrically-operated machinery in that the power can be easily and accurately measured, and it may be of interest to mention that portable graphic recorders are used in at least one colliery to check the working of electrical coal-cutters. Critical examination of the charts enables the management to compare the handling of the machine by different men and to correct errors of operation. The extraordinary conditions which have to be faced by the designer as if they were normal are well illustrated in the paper. Nature and man seem to conspire to destroy the machine, and I may illustrate this by reciting the circumstances of a fatal accident described in my Annual Report for 1924. A bar coal-cutting machine had become wedged between roof and floor in a 19-in. seam, and, in the attempt to free it by using the power of the motor, first the haulage drum was broken, next the haulage prop and then the haulage rope. The drum was designed with an adjustable slipping clutch to limit the stress and there were fuses in the circuit at the gate-end box, but these "safety valves" had been "attended to." The victim in this case was working under the direction of an under-official of the mine. The difficulty of maintaining flame-proof enclosures intact under conditions which this accident illustrates is indeed great. In the Prussian code of mining regulations there is a requirement that for underground use the covers of electrical apparatus shall be so fixed that they can only be removed by the use of a special tool. The principle implied is one that I have suggested to manufacturers here, i.e. that it should be made difficult for unauthorized persons to meddle with such enclosures. I am inclined to agree with Mr. Mavor's view that the permissibility of electrical equipment, i.e. the avoidance of the risk of explosion, lies rather with the maintenance of adequate ventilation than with the design of the electrical enclosure, but much may be done to facilitate proper maintenance.

Coming to Mr. Miller's paper, that there is a field for storage-battery locomotives in coal mines must be admitted in view of the considerable use made of such tractors in America and in Germany, and it is unfortunate that Mr. Miller has not been able to support his advocacy by figures of the actual operating costs. There are about a dozen collieries and half as many metalliferous mines in Britain where storage-battery locomotives have been introduced. In one of the latter the battery is also used to furnish the energy for operating rotary drills. Although the service required of locomotives is in no way comparable with that required of coal-face machinery, the same problem of proper maintenance must be faced by the management, for the battery is not amenable to design which can make it proof against continued misuse. Mr. Miller refers to the competition for a prize offered by Mr. Markham, a coal-owner, and as one of the judges in that competition I may say that our report will shortly be published by the Mines Department. Some of the provisions of our Specification were criticized on the ground that it would have been more logical to have adapted a mine to suit the characteristics of the storage-battery locomotive than to have called for a freak locomotive to meet the existing mining conditions, but the makers of coal-face machinery, as we have heard to-night, did not find that short cut to success, although one willingly agrees that to get the best results it is necessary to adapt or modify mining methods to the medium that is employed. The field trials of the locomotives proved, so far as the competing vehicles were concerned, the superior efficiency of the single-motor design, provided the design is skilful and adapted to the peculiar service conditions to be met. The prize-winning vehicle only required one-third of the capacity of the battery as compared with one-half for the next most efficient vehicle, while running over a test route which was designed to represent the average work of one shift. Autographic records, obtained with the assistance of Mr. George Watson's dynamometer, showed the rather surprising figure of 57 lb. per ton for the rolling resistance of the load. The actual draw-bar pull recorded ranged from 740 to 775 lb. with a load of 5 tons on a gradient of 1 in 24. On the subject of flame-proof enclosure, nothing better than total enclosure with plain machined flanges can be applied to the enclosure of electrical apparatus for which free ventilation is not essential. The use of gauze or of anything approximating in fragility to that medium should be avoided, and intricate devices, however ingenious, are quite unsuitable for colliery conditions as they exist to-day. Ventilation may be necessary for the battery; it is certainly not required elsewhere, and if some flame-proof ventilating device is employed it should be subject to the same sort of daily scrutiny as that which the miners' safety lamps undergo.

Coming to Mr. Nelson's paper, perhaps I can most usefully contribute to the discussion by supplementing the statistical data that he quotes, and I shall refer first to the proportion of mines without electrical equipment, for this varies widely in different parts of the coal-field. For example, in Scotland 72 per cent have electrical equipment as compared with less than 54 per cent for the rest of the country. In South

Wales and Monmouth 58 per cent are equipped, whilst for Northumberland and Durham the figure is 59½ per cent and for Nottinghamshire 88 per cent. South and West Yorkshire taken together approximate to South Wales, having 57½ per cent equipped. Taking North Staffordshire with Cannock Chase the figure is 55½ per cent, falling to 53 per cent for Lancashire and Cheshire and to less than 17 per cent for South Staffordshire and Worcestershire. The horse-power of electrical motors installed both above and below ground per mine also varies considerably in different areas. The average for the whole country is 910 h.p. Reviewing the 25 districts, mostly separate counties which are detailed in my annual report, there were 4 averaging 300 h.p. or thereabouts per mine, 9 averaging 600 h.p. or thereabouts, and 12 averaging from 900 to 1 600 h.p. per mine. As we have been discussing coal-cutting and other coal-face machinery it may be interesting if I give some figures showing the proportion of the total h.p. installed for these services. For the whole country the figure was 6·22 per cent; for Scotland alone the proportion was 16·6 per cent, and in South Wales two-thirds of 1 per cent. In the Newport and Cardiff division of South Wales 362 000 tons of coal were cut by electrical means and 2 070 000 tons by compressed air, out of a total of nearly 37 million tons got. In the Swansea division the position as to electricity and compressed air is reversed, 168 500 tons being cut by the former and 19 500 by the latter, out of a total of rather more than 15 million tons. All my figures refer to the year 1924. It can therefore be seen that, great as has been the growth of electrical equipment at collieries since 1912, there is still ample scope for development if and when the mining engineer succeeds in so controlling the natural conditions—where they are in his opinion at present antagonistic to the introduction of electricity—as to make it safe to do so. I suggest that the advantage of electricity in mining lies not so much in the lesser consumption of low-grade fuel for the production of the power, but in the greater output that can be obtained by its use and in the ease and flexibility, to use general terms, of its application.

Mr. Roger T. Smith: Mr. Miller points out in his paper that a case can only be made out in this country for the use of battery locomotives in thin seams, either for gathering or for marshalling, and that where there are thick seams the conveyor will beat the locomotive. I think, however, that that has yet to be proved, as there are so comparatively few battery locomotives in use, and, as Mr. Miller confesses, he has no figures to offer for working costs. Therefore we have yet to find out how many pit ponies, on the average, a locomotive can replace. On page 1004 Mr. Miller gives the limitations placed on the design. In the third limitation he says "ample clearance must be allowed underneath the locomotive to clear obstructions on the main haulage road." When, as in the Markham competition, the height of the locomotive is limited to 42 in. (which is about the height that will normally be necessary for a battery locomotive in this country), the wheel diameter cannot be greater than 22 in., and then only if worm gear is used. In the design that won the prize, worm gear was used, with that maximum diameter of wheel. In such a case it is quite easy to design a locomotive to clear all the obstructions which there are—tub-greasers, pulleys and other things—on the track. Mr. Miller, however, later on advocates chain gearing. If chain gearing is adopted the diameter of the wheel is decreased. Not only does chain gearing decrease the clearance but it adds the danger that in derailment the locomotive might be so placed across the rails that the whole or much of its weight comes on the gear case; and it is very expensive to design a gear case which will stand that. In limitation No. (4) the author says: "The locomotive must also be capable of giving sufficient adhesion to pull at least a load of 5 tons on a grade of 1 in 20 and have a speed on the level of about 3½ miles per hour when pulling the same load." I think he has been a little pessimistic in his speeds. It is quite easy to design a locomotive to pull 5 tons at 3½ m.p.h. up a gradient of 1 in 20, and to have a corresponding speed of 5 or 6 m.p.h. on the level. In the trials of the five locomotives for the Markham Prize every single locomotive which competed fulfilled that condition, which was one of the specified conditions, but with a gradient of 1 in 24 instead of 1 in 20. Mr. Horsley has dealt with the question of one electric motor as against two. I would only add that I think there is a very good reason why one motor should be more efficient than two from a consideration of their size. After all, in such little locomotives as were tested for the Markham Prize the one which won the prize had only an 8-h.p. motor, and when two motors of 4 h.p. are used the efficiency falls very considerably. It ought also to be mentioned that all the advice which Mr. Miller gives in his paper about the use of ball bearings and roller bearings on every possible rolling surface had been faithfully carried out in the winning locomotive, and it was due to that, as well as to the single motor, that it was so appreciably more efficient than any of the others.

Mr. W. B. Woodhouse: I have been interested in using power in mines for a good many years, and I know there has been a very marked change of practice. To-day, although air measurements are not general and although even electrical measurements are not as general as they should be, the mining engineer is beginning to measure accurately; and the more accurate he becomes in his measurements the more is he convinced of the advantages of certain pieces of apparatus such as the electrical cutters which Mr. Mavor has described. I think we owe him a debt of gratitude for having emphasized for so many years the importance of getting accurate data on which to base conclusions. The comparison of the amount of power taken by the electric coal-cutter and the compressed-air coal-cutter is perhaps an interesting comment on a recent statement which compared the relative efficiency of transmitting electricity and compressed air. I believe that compressed air was stated to be the more efficient and the more efficiently transmitted. The really important matter which was omitted and with which Mr. Mavor has dealt, was the efficiency of use.

As to Mr. Miller's paper, the use of electric batteries in coal mines in those parts of England in which I am interested is not, I think, likely to be very great, but there must be a field for them, and it is satisfactory to

know that electrical engineers are dealing with the matter so efficiently.

Mr. Nelson makes one reference which is of special interest to me, and that is to the question of the source of power for collieries. I found, as he says, that many estimates of the relative cost of producing power on the spot or buying it from somewhere else are made in the absence of measurement of the amount of power. I have been solemnly informed in many cases that the cost of production was a certain fraction of a penny, whereas I have discovered by observation that there were no means of arriving at the number of units used, that the total consumption was merely estimated, and that the price per unit was guessed at. With regard to estimating costs, I have found the difficulty as to capital charges which Mr. Nelson mentions, partly due to the habit of the mining people—which is perhaps also the habit of people in any fluctuating trade—of spending money when they have it and not making any regular allocation of capital charges. The principal obstacle in the way of a general adoption of a public supply of electricity has, I think, been the steam winder. The very high cost of electric winders before the war was an obstacle. There was the additional obstacle to which Mr. Nelson refers, namely, the absence of a sufficiently powerful system of public supply to deal with winders. To-day, however, we have large systems with very large amounts of power behind them, and the fluctuation of load due to a 1 000- or 2 000-h.p. winder is negligible; the system can deal with it. Therefore we can use, and are using, three-phase winders at a much reduced first cost. I feel sure that as existing steam winders fall out of use, and as the complications and inefficiency of the exhaust turbine steam-winder combination become emphasized by age, the number of pits without any steam at all will increase and the public supply will be more and more used.

Mr. E. T. Williams: I should like to support Mr. Mavor's contention with reference to the inefficiency of compressed air. Extensive experience of compressed air and electrical operations running side by side has convinced me that those who used compressed air very often failed to realize the true factors. It was only when those factors were pointed out to them by technical people that they realized how great was the inefficiency of the compressed-air systems. One point alone which they often overlooked was that where there were very long compressed-air pipe lines there were often a large number of small leakages. These small leakages in the aggregate constituted a very large loss in a 24-hour day. In connection with cables, we know it is a serious problem to get cables to withstand the arduous conditions in mines. I may state that a cable has been devised for the use of the Navy in which a tough rubber sheathing is reinforced with a cord canvas. We have carried out a great many trials both in the works and at sea, and this cable has given most satisfactory results. I think that mining engineers should know of this recent advance in cable design.

I believe that we are coming to a transition period when things are going to change very much in both coal-mining and in electricity supply. Referring to Mr. Nelson's paper, in his summary he says: "The conclusion is ultimately drawn that one-half the motive power of the mines of Great Britain still remains non-electric." Then in Mr. Mavor's paper there is the remark: "It must be accepted that electricity will continue to be excluded from the coal face in many collieries, but the number of these may be reduced by fuller knowledge," and in the very last paragraph of the paper it is stated: "By mechanical and electrical aids to production the output per man can be increased, wages and the status of the miner can be raised, and the cost and price of coal can be reduced." I should like to submit that the importance of the coal industry to this country, the economic crisis through which we are passing, and the new developments which are about to take place electrically, are such that the Council should consider the appointment of a Committee to examine the question of how the use of electricity in mines might be extended and developed.

Mr. F. T. Hall: I should like to ask Mr. Mavor if it is now the practice in any of the mines where it is not considered safe by the management to have electric coal-cutters at the face, to employ an electrically driven compressor in some neighbouring place which is well ventilated. In my early days I was employed by a company which did a good deal of pioneer work on coal-cutters, and we found it was expedient sometimes to get in by that means. One of our arguments was that we thereby improved the ventilation at the face by the exhaust from the compressor.

Dr. W. M. Thornton: My feeling is that, in its flexibility and efficiency, electricity is really ideal for mines. If there were no such thing as gas in mines, electricity would be universally used. Therefore the question really resolves itself into one of safety. My own feeling is that where there is gas, electricity ought not to be used except at voltages at which it is more than usually safe—25 volts, for example. If it were practicable to run a flood-lighting system at 25 volts at the face I am quite sure it would have an extraordinary beneficial effect in mining, especially from the psychological point of view. I take it that underground we are still in the candle-light stage. When we are able to get underground the same amount of lighting as we have in this lecture theatre I think the psychological effect and stimulus will be very great. With regard to the use of locomotives, I think the chief motive has been a humanitarian one rather than any question of economy in haulage. I suggest that there is a very important field still to be worked with regard to mining, and that is in connection with the education of the young miner. Mr. Horsley and other speakers have said that one thing which is acting against the use of electricity in mines at the present time is imperfect maintenance. It will never be possible to ensure maintenance until those who are working with the apparatus have a thorough knowledge of it. When that happens there will not be those deplorable slips in maintenance with which we are all familiar at the present time. I suggest that this question of education might be taken up, if not by this Institution then by some allied Association.

Mr. C. E. Sayer: At the end of his paper Mr. Mavor says, after speaking of the services which the mechanical

and electrical engineer have rendered to the mining industry: " The output per underground worker is too low, therefore too many men are in the industry—that is why wages are low and costs are high." This seems rather to support the case of the average worker, that if they abandon the " go-slow " principle they will cause more unemployment by throwing men out of work. This perhaps might be better expressed by saying that under existing conditions there are too many men in any given pit, and that by the adoption of more mechanical processes in the coal-field and raising the output per man the return obtainable from mining would become so increased that, although fewer men would be required in any given pit for its present total output, the balance would be adjusted, and the number of men employed in the industry would even be increased by the impetus which would be given to coal-mining in general.

Mr. Christopher Jones: Mr. Horsley has raised some very interesting points, one in particular referring to the Prussian Government specification regarding concealed bolts and nuts. This could with advantage be taken up by British manufacturers in connection with coal-cutter and conveying machinery, as my experience is that it is quite common for the engineer in charge to have to be continually instructing workmen as to the necessity of making sure that all such bolts and nuts are in proper order. The question of using recording meters in connection with coal-cutter circuits is also very interesting. Certainly such meters are of great assistance in checking consumption in the operation of the machines, as pointed out by Mr. Mavor in regard to faulty picks. It is, however, not always convenient to adopt such instruments inbye in mines, owing to their delicacy. I should like to know whether an inkless type of recording meter is made. We are now introducing portable watt-hour meters in connection with gate-end switches for this purpose. Mr. Mavor has not referred to the Arcwall machine, which is a type now being largely introduced in the mines. With such machines the question of a proper design of trailing cable is a very important matter. I have been a strong advocate of a trailing cable designed with all cores protected by means of Ferflex braiding and have had one in use successfully for three years, but recent supplies of similar cable have proved unsatisfactory. Such cables are trailed considerable distances when 30 to 40 heads are cut per shift. Mr. Williams has referred to a special cable used by the Admiralty and I should be glad to have further particulars of this type. Mr. Mavor has referred to the electric rock drill as not being a success. This is also my experience and mining engineers would welcome a design similar in weight to the compressed-air rock and coal drill as it generally means the installation of an inbye compressor, and, with the advent of coal-cutters and conveyors, hand-drilling operations for blasting purposes delay matters considerably. Mr. Mavor refers to the increased use of coal-cutters since the introduction of alternating current to the mines, but I know of a d.c. coal-cutter installation which has been running successfully for the past 16 years. Mr. Foggo, the manager of Cannock Chase Colliery, has recently been to the United States investigating machine mining. He informs me that most of the installations which he visited had d.c. supplies.

With regard to electric locomotives generally, the conditions in this country are not suitable for adopting these without a great deal of expenditure in alteration of roadways and the replacement of light rails by those of heavier type, which is found necessary. For new mines no doubt there is a large field and a good case can be made for the introduction of such locomotives.

I am in general agreement with the points raised in Mr. Nelson's paper.

Mr. H. Rainford (*communicated*): Under the heading of " Flame-proof enclosure of the electrical gear," Mr. Miller draws attention to the Safety in Mines Research Board Paper No. 5, by Statham and Wheeler, on " Flange Protection." He states that although Messrs. Statham and Wheeler have not dealt with the alternative methods of protection, the matter has been dealt with by the American Bureau of Mines and several Continental investigators. I should like to take this opportunity, therefore, of pointing out that the report on " Flange Protection " was Part I of a research on " Flame-proof electrical apparatus " and that since its publication a considerable amount of work has been done by the Safety in Mines Research Board in conjunction with the British Electrical and Allied Industries Research Association on the alternative methods of protection. Experimental work has been carried out on gauze and perforated-plate protection and a report on this work is now in course of publication as Part II of the researches already mentioned. Experimental work has also recently been completed on a " Plate protective device " of the " annular ring " type, and a report on this device is in the hands of the E.R.A. The author states that nowadays none of these alternative methods is being used, reliance being placed almost entirely on flange protection. Whilst, undoubtedly, flange protection is used in a large number of instances, it is worth while noting that of the pieces of apparatus which have been tested for " flame-proofness " by the Mining Department of Sheffield University (under the direction of Professor Statham) quite a number (33 per cent during the past twelve months) have been fitted with other protective devices. In particular the plate protective device, both of the rectangular-plate and annular-ring types, has been used quite successfully. With regard to the strength of these devices, the gauze and perforated-plate types are undoubtedly mechanically weak and it is necessary to protect them by means of some form of wire grid or spring cover. The plate-protective device of the annular-ring type, however, is of a robust nature, the rings being assembled by threading them on bolts and spacing them apart by means of washers. To keep the rings in position and to close the inner hole, a strong metal plate is bolted down to them. This plate, especially if it is extended down the sides of the rings in the form of an inverted metal cap, gives ample protection to the rings from damage by outside forces. The question of incorrect assembly of any of these devices depends entirely on the maintenance of the apparatus and it is essential that flame-proof apparatus should be periodically examined by one who can

appreciate the difference between a flame-proof enclosure and an ordinary enclosure, and who is familiar with the devices used. Mr. Miller raises the important question of the evolution of hydrogen in the battery casing of the locomotive, when the battery is being charged. Ventilation of the casing is therefore important and it is suggested that one or more flame-proof relief devices could be mounted on the casing, so arranged that the windage of the motor would promote ventilation through them.

The Authors' Replies to the Discussion.

Mr. S. Mavor (*in reply*) : The discussion on my paper, being chiefly supplementary, calls for cordial acknowledgment to the contributors and only brief reply. Mr. Horsley and Mr. Woodhouse emphasize the value of measurement, especially by recording instruments. Graphic records both of pressures and quantities of electricity and compressed air, when interpreted with intimate knowledge of the nature of the operations concerned, are most instructive and suggestive guides to improved efficiency in application of such machines as coal-cutters and conveyors, and also to economy in the use of power.

In reply to Mr. Hall's question regarding the use of inbye air-compressors for the supply of compressed air to coal-cutters, it may be said that this arrangement is technically, but not economically, feasible. It is necessary with such an arrangement that the power of the motor driving the compressor shall be between 3 and 4 times the power to be developed by the coal-cutter ; the stand-by losses and light-load losses, even when automatic control gear is used, are further handicaps. The arrangement referred to has been tried in a few cases, but so far as I know no example survives in service. Many portable or semi-portable electrically-driven inbye compressors of comparatively small size are used for power supply to percussive drills. The drills, one or two from each compressor, are for boring shot-holes in the coal face, or for shot-holes in stone ripped to make height in roadways. When compressed-air drills are used in the confined space of a heading the air exhausted from them contributes materially to ventilation ; but in the case of a longwall coal-cutter, although it uses from 6 to 12 times the amount of air required by a drill, the volume of air exhausted is so little compared with the ventilating air current that is swept along the face, that its effect on ventilation is almost negligible.

Mr. L. Miller (*in reply*) : I am very glad to hear that Mr. Horsley is of opinion that there is a field for battery locomotives. I presume he agrees that their application will be considered in such cases where the conveyor system would not be justified on the score of expense. I agree with Mr. Horsley that it would be economically impossible to ask the collieries to re-design their roadways to suit the battery locomotive.

Mr. Horsley and Mr. Roger Smith both refer to the trials of the Markham Competition locomotives as having proved, as far as the competing vehicles were concerned, that the single-motor drive was more efficient. Mr. Roger Smith is of opinion that the better performance obtained was partly due to the higher efficiency of a single 8-h.p. motor as compared to two 4-h.p. motors, but I have read through the report of the trials and I cannot agree with the conclusion that both these gentlemen have arrived at. In the first case I should like to point out that the winning locomotive was not the only single-motor design tested ; there was at least one other that competed in the trials. This, however, had a very much larger consumption than the two-motor design ; therefore, on the face of it, the conclusion that a single-motor design is more efficient cannot be arrived at as a result of these tests. As a matter of fact, a single 8-h.p. motor as compared with a 4-h.p. motor of a design that will be used on such a locomotive would have a higher efficiency. This difference of efficiency would amount to at the most about 4 per cent. I should like to add that all I claim for the two-motor design is that it enables resistances to be done away with. I think that Mr. Horsley and Mr. Roger Smith will both agree that it is possible to absorb considerably more than 4 per cent in resistances if very much manœuvring at low speeds has to be done. I think that the results obtained with the other single-motor drive partly prove this. Apart from this, however, there is the resistance to be accommodated on the locomotive. This has to be fitted in a flame-proof cover and should be ventilated if it is to be kept to reasonable dimensions. This is not a difficult thing to accomplish but it adds a piece of apparatus which is likely to break down unless made of very considerable dimensions. It is only fair to observe that the enclosure of the resistances on the winning locomotive was not flame-proof.

Mr. Horsley refers to the consumption figures obtained on the locomotive trials. I am definitely of opinion that such consumption figures are of very little value as far as a comparison of the locomotive is concerned. I presume there is some reason why so much importance was attached to these consumption figures but, as I explained in the first part of the paper, the cost of power is such a very small item in colliery costs that the power consumed by these locomotives cannot have any bearing on them. The only advantage a lower consumption gives is a reduction in the size of the battery. These figures appear to have been regarded as a measure of the efficiency of the locomotive and it appears to have been forgotten that they also include a measure of the efficiency of the driver and to a certain extent a measure of the condition of the rails. For instance, if the rails are greasy due to rain, slipping will take place and power will be lost. If the single-motor drive having the very large consumption be compared with the winner, since the power required to pull the load must be the same, it is quite impossible to believe that this difference is due to the higher efficiency of the motor, gearing and axle bearings on the winning locomotive. The motor may be responsible for 2 per cent difference, the gearing for perhaps 3 per cent, and even assuming the axle bearings to take 57 lb. per ton to

overcome friction, such a figure could not be obtained for the consumption unless the driver were running on resistance notches for a large proportion of the time and not taking full advantage of coasting at the ends of the journeys and wherever possible. This is an example of very bad driving. The winning locomotive is an example of extremely efficient driving. To prove this I have analysed the figures for the winning locomotive. In making this analysis I have taken a load of 5·03 tons over the test route as shown in the chart attached to the report. The calculation is as follows :—

Power consumption for 30 trips consisting of 10 trips on each of the 3 routes shown on the plan attached to the judges' report of the trials of mining locomotives entered for the Markham Competition.

Weight of locomotive = 3·15 tons.
Weight of load = 5·03 tons.

Total weight = 8·18 tons.

I shall ignore the power required to drive the locomotive and take the drawbar pull as 57 lb. per ton as given in Mr. Watson's report.

Route (1) *including water-splash*.—This is the route on which the two diagrams showing the pull were obtained by Mr. Watson.

Section (*a*). 57 yds. ; 1 in 30 gradient.

Outward journey :

Work done (friction) (ft.-lb.)

$$= 57 \times 5{\cdot}03 \times 57 \times 3 \times 10 = 490\,274$$

Work done (gravity)

$$= \frac{8{\cdot}18 \times 2\,240}{30} \times 57 \times 3 \times 10 = 1\,045\,000$$

Inward journey : Train coasts.

Section (*b*). 50 yds. ; 1 in 24 gradient.

Outward journey :

Work done (friction)

$$= 57 \times 5{\cdot}03 \times 50 \times 3 \times 10 = 430\,000$$

Work done (gravity)

$$= \frac{8{\cdot}18 \times 2\,240}{24} \times 50 \times 3 \times 10 = 1\,146\,000$$

Inward journey : Train coasts.

Section (*c*). 100 yds. level.

Outward journey :

Work done (friction)

$$= 57 \times 5{\cdot}03 \times 100 \times 3 \times 10 = 860\,130$$

Inward journey :

Work done (friction)

$$= 57 \times 5{\cdot}03 \times 100 \times 3 \times 10 = 860\,130$$

Total 4 831 534

This figure ignores flange friction at curves.

If we take the diagrams prepared by Mr. Watson showing the pull required for this route, the average pull for the first test comes out at 555 lb. and for the second test at 568 lb. (average 560 lb.). This is only for the outward journeys.

∴ Work done

$$= 207 \times 3 \times 10 \times 560 + 860\,000 = 4\,340\,000 \text{ ft.-lb.}$$

This checks as closely as can be expected with the first figure obtained of 4 831 534 ft.-lb. Since the latter figure is, however, likely to be more accurate this will be taken for the purpose of the calculation.

$$\text{Consumption} = \frac{4\,340\,000}{2\,650\,000} = 1{\cdot}64 \text{ kWh}$$

Route (2).—This is the route proceeding up the same road as No. 1 but turning off at about the centre.

Section (*a*). 57 yds. ; 1 in 30 gradient.

Outward journey :

Work done (friction and gravity)—same as Section (*a*) (Route 1) = 1 535 274 ft.-lb.

Inward journey : Train coasts.

Section (*b*). 100 yds. ; 1 in 72 gradient.

Outward journey :

Work done (friction)

$$= 57 \times 5{\cdot}03 \times 100 \times 3 \times 10 = 860\,130$$

Work done (gravity)

$$= \frac{8{\cdot}18 \times 2\,240}{72} \times 100 \times 3 \times 10 = 763\,440$$

Inward journey :

$$\left[(57 \times 5{\cdot}03) - \frac{(8{\cdot}18 \times 2\,240)}{72}\right] \times 100 \times 3 \times 10 = 96\,000$$

3 254 844

No diagram is given for this route so that this cannot be checked.

$$\text{Consumption} = \frac{3\,254\,844}{2\,650\,000} = 1{\cdot}23 \text{ kWh}$$

Route (3).—This is the route along the road marked " Main Haulage Road " on the plan.

132 yds. ; 1 in 36 gradient.

Outward journey :

Work done (friction) (ft.-lb.)

$$= 57 \times 5{\cdot}03 \times 132 \times 3 \times 10 = 1\,135\,371$$

Work done (gravity)

$$= \frac{8{\cdot}18 \times 2\,240}{36} \times 132 \times 3 \times 10 = 2\,016\,000$$

3 151 371

Inward journey : Train coasts.

$$\text{Consumption} = \frac{3\,151\,371}{2\,650\,000} = 1{\cdot}19 \text{ kWh}$$

Total kWh for 30 journeys over 3 routes :—

	kWh
Route (1)	1·64
„ (2)	1·23
„ (3)	1·1
	4·06

If this is reduced in the ratio of miles calculated to miles given in schedule, the figure becomes

$$\frac{5\cdot 36}{5\cdot 63} \times \frac{4\cdot 06}{1} = 3\cdot 87 \text{ kWh.}$$

In making this calculation it will be observed that no allowance at all has been made for the friction of the locomotive axles, flange friction of the locomotive, losses in braking at the end of the journeys, and losses in resistances, motors and gearing; also the mileage appears to be slightly different from that given in the schedule.

In the case worked out above a mileage of **3·95** with power and **1·68** coasting, totalling **5·63** miles, has been included; the figures given for mileage in the schedule are **3·25** miles with power, **2·11** miles coasting, giving a total of 5·36 miles. It would appear from these latter figures that the gradient of 1 in 72 has been included as one on which coasting can be accomplished; this is not true, however, if a train resistance of 57 lb. per ton is experienced. However, since the mileage given in the schedule is slightly different, the total kWh have been adjusted in proportion and become **3·87** kWh for the load.

The motors of the size employed on these locomotives will have an efficiency of not higher than 87 per cent, and the gearing, including connecting rods, etc., cannot have a much higher efficiency than 95 per cent. The energy at the axle of the locomotive will therefore be $5\cdot 7 \times 0\cdot 87 \times 0\cdot 95 = 4\cdot 7$ kWh. Subtracting from this the energy required to move the load, which is **3·87** kWh, 0·83 kWh is left to overcome locomotive friction, losses in the resistances, energy loss in braking at the ends of the journeys and flange friction of the locomotive. This indicates a very remarkable performance on the part of the driver, especially when it is realized that if the whole of this power was absorbed in friction at the axles and flange friction it only represents a resistance of 35 lb. per ton for the locomotive.

Such an analysis as is made here on the trial figures can only be approximate on the data which is available, and is only intended to show that great importance cannot be attached to them. It seems a pity that while the trial track and locomotives were available, considerably more detailed information was not obtained and that the report did not analyse more fully the data so as to indicate where losses were taking place. An opportunity appears to have been missed to obtain very valuable design data.

It is also quite clear that the ball bearings on the locomotive have had an even larger influence in reducing the consumption than has been indicated in the paper. The losses due to wheels slipping must be very small indeed and the track must have been in perfect condition. It is also perfectly clear that practically no losses have taken place in the resistances and that the driver never ran for any length of time on the resistance notches. This is a condition which would not obtain in practice and therefore these figures cannot be used to prove that the two-motor design is less efficient in actual operation than the single motor.

With regard to the question of flame-proof enclosure, I am glad to see that Mr. Horsley agrees with me that plain machine flanges represent the best solution of this problem.

I quite agree with Mr. Roger Smith that the statement made with regard to the scope of the battery locomotive in this country is only an expression of opinion and has yet to be proved. With regard to the question of wheel diameter, I should like to point out that if a wheel diameter of 22 in. is adopted this will result in a reduction in the height of the battery box which is certainly not desirable on a locomotive performing the rough service which this mining locomotive will be called upon to do. I cannot follow Mr. Roger Smith in his argument that the adoption of chain gearing restricts the size of the driving wheel; the restriction to the size of the wheel is in the height of the battery box, not the adoption of chain drive. I also do not agree with Mr. Roger Smith in his assumption that in the case of derailment the gear case enclosing the chain drive is likely to get damaged. There is no difficulty in avoiding any danger of damage to the gear due to such an accident. There is, however, some slight difficulty in avoiding a similar danger with the connecting rod which is usually employed with the single-motor drive. Mr. Roger Smith is quite correct with regard to the question of speed. The 3½ miles per hour given in the paper is a figure put in so as not to clash with a similar figure given in the specification issued for the Markham Competition. The desirable speed will depend very greatly on the type of mine in which the locomotive is to be installed, but in the majority of cases it is advantageous to run at a higher speed than the one given. The final point which Mr. Roger Smith raises has been dealt with in the reply to Mr. Horsley's remarks.

With regard to Dr. Thornton's remarks, I think that Mr. Markham was certainly influenced from the humanitarian point of view in offering a prize, but, of course, there is always the question of economy to consider.

I do not entirely agree with Mr. Jones with regard to the question of the expenditure entailed in altering roadways and replacing light rails when it is intended to use a locomotive. This may be true of certain pits, but in others a locomotive can be substituted with practically no alteration at all to the weight of rails. A locomotive of the type suggested in the paper will function on almost any colliery rail.

With regard to Mr. Rainford's remarks, I was referring to the time at which the paper was written when I made the statement that Messrs. Statham and Wheeler had not dealt with the alternative method of protection. I knew that their report on flange protection would be followed by further reports. Mr. Rainford credits me with saying that none of the alternative methods is being used. This is incorrect; the statement made was as follows: "It is significant that 15 years ago manufacturers were experimenting with devices of this kind, but nowadays none of these are being used by the people concerned in these experiments. They have practically all adopted flange protection." It is the people who were conducting experiments 15 years ago who have adopted flange protection and I think I am correct in this statement.

I have read Mr. Rainford's description of the plate protecting device which is similar to one experimented

with many years ago. I am still of opinion that in ordinary colliery service such a device is not satisfactory.

With regard to the battery casing, surely the easiest way is to provide the whole casing with a sufficiently wide flange to enable a reasonable gap to be maintained which will be sufficient to provide ample ventilation and yet maintain its flame-proof characteristic.

Mr. R. Nelson (*in reply*) : In replying to the short discussion on my paper, I should like first to make the general comment that no one appeared to differ from the view expressed on the main point I tried to make, namely that it is better in most cases to purchase current, where that procedure is possible, than to generate it. Apart from this, I have chiefly to acknowledge contributions from various speakers, notably Mr. Horsley and Mr. Woodhouse, to the general information on the subject matter of the paper. It is clear from the data given by Mr. Mavor on the subject of machine mining in Scotland, supplemented by Mr. Horsley's statistics for the rest of the country, that Scotland at any rate compares favourably with America in the matter of the use of coal-face machinery. That fact is encouraging, even if certain of the English districts still lag well behind. Mr. Horsley will perhaps allow me to repeat and endorse his last observation, which was to the effect that the advantage of electricity in mining lies mainly in the greater output that can be obtained by its use and in the ease and flexibility of its application.

One of Mr. Woodhouse's most interesting statements was that in which he expressed the belief that as the complications and inefficiencies of the once fashionable steam-winder and exhaust-turbine combination become emphasized by age, the number of pits without any steam at all will increase and the public supply will be more and more used. That statement will, I think, prove to be a correct forecast of future development.

Mr. Williams directed attention to a conclusion drawn by me from published statistics, namely that about one-half the motive power of the mines of Great Britain still remains non-electric, and also to two statements by Mr. Mavor, namely that " it must be accepted that electricity will continue to be excluded from the coal face in many collieries, but the number of these may be reduced by fuller knowledge," and that " by mechanical and electrical aids to production the output per man can be increased, wages and the status of the miner can be raised, and the cost and price of coal can be reduced." Mr. Williams went on to suggest that the Council of this Institution might consider the appointment of a Committee to examine the question of how far the extended use of electricity in mines might assist the mining industry in its present difficulties. That is, I think, an interesting and helpful suggestion, but one which would be more likely to have a practical result if the Institution of Mining Engineers could be induced to assist by appointing one-half of such a Joint Committee of investigation.

In acknowledging Dr. Thornton's contribution, I only desire to endorse his view that flood-lighting a coal face would probably have important psychological as well as practical results. The chief difficulty of the miner's occupation, and the direction in which he most deserves sympathy and consideration, arises from the dim, uncertain light in which he is obliged to spend the greater part of each working day. . It is probable that better lighting below ground, progressively introduced, as no doubt it will be, will tend definitely to diminish "absenteeism," which, as the Royal Commission's Report shows, is one of the major difficulties of the mining industry.

It is gratifying to me to find general support for the views and opinions expressed in the paper.

THE FREQUENCY CHARACTERISTICS OF TELEPHONE SYSTEMS AND AUDIO-FREQUENCY APPARATUS, AND THEIR MEASUREMENT.

By B. S. Cohen, Member, A. J. Aldridge, Associate Member, and W. West, B.A., Student.

(*Paper first received* 19*th January, and in final form* 23*rd March,* 1926; *read before* The Institution 29*th April,* 1926.)

Summary.

The value is demonstrated of the frequency/amplitude characteristics of telephone systems or apparatus in determining the transmission efficiency, including volume and articulation efficiency. The audio-frequency ranges of importance for speech and music are then considered.

Methods are described for the direct and indirect production of constant acoustic output over the audio range, and the calibration of acoustic measuring instruments is dealt with.

The next section of the paper deals with the production of electrical energy of constant value over the required frequency range, and a description is given of a special form of oscillator, together with associated apparatus for the direct recording of frequency characteristics.

The concluding part of the paper gives frequency characteristics of each part of the apparatus used in a telephone connection, and also of audio-frequency amplifiers and loud-speakers. For the purely electrical portions of the circuit, current or voltage characteristics are given, whilst for apparatus such as transmitters and receivers the characteristics are given in terms of acoustic pressures on the diaphragm. The characteristics of some commercial types of granular transmitters are first given, then under the heading of receivers will be found the characteristics of both the Bell pattern and some typical loud-speakers of the horn and hornless types. Particulars are given of apparatus designed to measure diaphragm motion, some results obtained by an aural balancing method being included.

In the section dealing with lines will be found characteristics for unloaded open wires and cables and for loaded cables. An impedance/frequency characteristic is also given and its application to fault location illustrated.

Some notes on telephone line repeater characteristics are included, and the next section deals with exchange cord circuits and subscriber's instrument characteristics.

Under audio-frequency amplifiers some typical intervalve transformers of the type used for broadcast reception are characterized, and an extension is given of the theory of this type of transformer covering the effects of resistance and capacity loads.

Introduction.

The determination of the transmission efficiency of telephone lines, circuits and apparatus is of fundamental importance in telephone engineering. Many electrical and acoustical problems are involved in the efficient transmission of speech, and these problems become more severe when efficient transmission of music is also required, as for example, owing to the use of land lines in connection with simultaneous broadcasting.

With respect to the development of wireless telephone apparatus, the radio engineer has to deal with problems similar to those involved in the transmission efficiency of wire telephony systems.

It may correctly be stated that the frequency/amplitude characteristic of a telephone system or of its component parts over the audio-frequency range required for efficient reproduction of speech and music, is a record of primary importance in determining the transmission efficiency of the system or component part in question. This will include both the volume and articulation efficiencies.

Volume may be stated to be a function of the amplitude of the frequency characteristic, whilst articulation is a function of the perfection of reproduction of the originating wave-form. It is not such a definitely quantitative factor as volume.

In the case of the transmission of ordinary telephone messages, it is obvious that these may be accurately received, even when the wave-forms are badly distorted, by the efficient co-operation of the receiving ear and brain.

When the context does not form an idea, such as in transmitting code messages and isolated words or sounds, the articulation of the system requires to be at a much higher level for efficient reception.

Perfect reproduction of the originating wave-form necessitates a system with a uniform frequency response or frequency characteristic at all volume-levels with which such a system is employed.

In addition, when transmitting drama, or vocal and instrumental music, the frequency response should not only be uniform but also approximate to the input level, so that the ratio of input to output over the audio-frequency range should approximate to unity.

Naturalness is also a factor of importance in the transmission and reception of music, etc., but one which does not necessarily enter into consideration of intelligibility. As a result of the elimination, reduction or amplification of single frequencies or bands of frequencies, unnatural and unpleasing reproduction may be obtained which, however, may be of high efficiency from the standpoint of intelligibility.

If, with any particular frequency and volume, an overtone is produced, this is termed non-linear distortion. This form of distortion will be produced by the overloading of transmitters, transformers, amplifiers and receivers (particularly loud-speakers, owing to the greater liability of their being overloaded). A further form of distortion is that due to the persistence of particular frequencies after the stimulus has finished, due to insufficient damping.

Whilst in connection with the production of basic reference telephone standards it is desirable that the transmitting, attenuating and receiving portions should have uniform frequency characteristics, it is frequently necessary to have the frequency characteristics of receiving apparatus, amplifiers, repeaters, etc., so shaped as to compensate for distortion which may be unavoidable in lines or transmitting apparatus.

Frequency and Amplitude Range of Speech and Music.

It has been shown that speech energy extends from a little below 100 cycles up to 6 000 cycles per second, i.e. a range of 6 octaves, and the range for music is somewhat greater.*

Experiments with high- and low-pass filters indicate that good-quality speech is transmitted by a telephone system with an upper cut-off point of about 2 500 cycles, and a system which faithfully transmits up to 5 000 cycles is practically perfect for speech and is good for music, although by no means perfect.

It is probable that a system with a cut-off lying between 5 000 cycles and 10 000 cycles, and nearer to the higher value than to the lower, is required for practically perfect music transmission. The exact value does not appear to have yet been definitely ascertained.

With regard to lower cut-off points, a system cutting off at frequencies below 500 cycles gives very high-grade articulation for speech but unsatisfactory and colourless reproduction of music. Frequencies down to 50 cycles are required for the perfect reproduction of instrumental music.

The mean frequency in speech from the articulation standpoint is about 1 500 cycles. That is to say, a system with a cut-off of all frequencies above 1 500 cycles gives the same quality articulation as one cutting off all below this frequency.

R. L. Jones also finds that a system transmitting only up to 1 000 cycles gives 40 per cent articulation, whilst a system transmitting all above 1 000 cycles gives 86 per cent articulation. The maximum energy for English speech has been found to occur at about 200 cycles and to fall off very rapidly below, and more slowly above, this frequency. If the average energy is expressed by the numeric 6 at 200 cycles, it has fallen to 3 at 400 cycles, 2 at 800 cycles, and 1 at 1 200 cycles. From thence to 5 000 cycles it remains at an average level of 0·5.†

With a normal voice the average speech power entering a telephone transmitter is about 100 ergs per sec., or 10 microwatts; owing, however, to the high mechanical impedance of the diaphragm only a fraction of this performs useful work. Some interesting measurements of the acoustical power of certain sound sources in absolute units were made by Paul E. Sabine.*

A violoncello bowed strongly had an acoustic output varying from 1 000 ergs per sec. at 128 cycles to 10 ergs per sec. at 650 cycles.

A good violin gave a fairly uniform output of 600 ergs per sec. between 192 cycles and 1 300 cycles.

A male voice intoning 12 vowel sounds at conversational loudness with a fundamental of 129 cycles had an output of 56 ergs per sec. approximately.

A female voice intoning a vowel with a fundamental of 258 cycles had an output of 40 ergs per sec. at conversational volume. With the voice raised to suit a small audience, the output was 145 ergs per sec. and when speaking loudly a maximum of 510 ergs per sec. was reached.

Response of the Ear to Variations in the Frequency and Intensity of Sounds.

A knowledge of the characteristics of the ear is necessary in order to arrive at a correct interpretation of the comparative effects of various frequency characteristics. Much work has been done in the last few years on this subject, particularly in America, and some data and references follow :—

The minimum sound intensity, often termed the "threshold of audibility," for a normal ear varies from an acoustic pressure of 0·15 dyne per cm^2 at 60 cycles to 0·001 dyne per cm^2 at 1 000 cycles. Between 1 000 cycles and 4 000 cycles the sensitivity remains approximately constant at 0·001 dyne per cm^2.†

Harvey Fletcher ‡ determines the sensitivity of the normal ear by averaging the results of Wien (1903), Fletcher and Wegel (1922) and Kranz (1923), weighted 3, 72, and 14 in accordance with the number of ears tested, and obtains the values shown in Table 1.

Table 1.

Frequency in cycles per sec. ..	64	128	256	512	1 024	2 048	4 096
Sensitivity in dynes per cm^2 ..	0·12	0·021	0·0039	0·001	0·00052	0·00041	0·00042

These notes only refer to a few of the acoustical values of importance from the telephonic standpoint. A list of the more important recent papers dealing with this subject will be found in the bibliography at the end of this paper.

Production of Constant Acoustic Output over Audio Range.

For the proper examination of the output of a transmitter it is necessary to have a reliable source of acoustic energy to put into the transmitter and one which can be measured and is of suitable magnitude,

* R. L. Jones: "The Nature of Language," *Journal of the American Institute of Electrical Engineers*, 1924, vol. 43, p. 321.
† I. B. Crandall and D. MacKenzie: "Analysis of the Energy Distribution in Speech," *Physical Review*, 1922, vol. 19, p. 221.

* *Physical Review*, 1923, vol. 22, p. 303.
† H. Fletcher and R. L. Wegel: "The Frequency-Sensitivity of Normal Ears," *Physical Review*, 1922, vol. 19, p. 553.
‡ *The Bell System Technical Journal*, 1925, vol. 4, p. 375.

and a means of measuring the resultant electrical output. For a receiver the conditions are reversed. A great many devices can be used which are completely reversible, that is, are capable of emitting acoustic energy when electrically excited, and vice versa, and a device which can be used either as a transmitter or as a receiver would obviously be the most suitable one to adopt.

To obtain frequency characteristics of transmitters and receivers the following are the necessary requirements :

(1) Apparatus producing approximately constant acoustic output over the required frequency range, for energizing transmitters.
(2) Apparatus having approximately constant acoustic "pick-up" efficiency, for measuring the output of receivers.
(3) Means for measuring and, possibly, photographically recording the acoustic and electric quantities over the range.

Direct acoustic generators.—For the excitation of transmitters the simplest method would appear to be the direct production of sounds from wind instruments. Organ pipes are stated to produce pure tones when blown with a constant air pressure, provided this is small, but they are very inconvenient in practical use. A large pipe would be required to produce a reasonable volume of sound, and it is awkward to handle; another serious objection lies in the fact that a series of pipes would be required to produce sounds of different frequencies, which, moreover, could not be continuously varied. Organ pipes are also difficult to calibrate absolutely as to the volume output by the only means which is at present available, viz. a Rayleigh disc, on account of the large air disturbances in the neighbourhood of an operating pipe.

A more promising instrument would appear to be a centrifugal type of siren. This, when driven at a constant speed under constant atmospheric conditions, will give a constant output of considerable intensity; the frequency is, however, directly dependent upon the speed, so that whilst a continuously variable frequency is possible the volume of the sound produced increases with the speed and frequency.

Some attempts were made to produce a siren of this type, not so much for use in the examination of frequency characteristics as to obtain a source of sound energy of constant value. It was abandoned on account of the difficulty experienced in designing a siren to give a note of single frequency. A siren built with openings which varied in area according to a sine function with time would, it was suggested, produce a pure note. This was found to be far from the case, due in all probability to the fact that the volume of air issuing from the orifices will only be proportional to the area of the opening if there is available a considerable reservoir of air under pressure, and if the speed be low.

Toothed-wheel sirens with teeth cut to special shapes and periodically obstructing a jet of air under constant pressure have also been suggested and tested. The difficulty with these devices, apart from the question of elimination of harmonics, is in avoidance of hissing effects from the eddies in the air jet and of vibrations at the edges of the wheels.

Specially designed whistles have been proposed as standards of sound, but they are unsuitable for the lower audible frequencies, the frequency is not continuously variable in any convenient manner, and the wave-form is bad.

Vibrating bars and tuning forks have been suggested, but very large instruments would be necessary to obtain a reasonable volume of sound, involving massive base plates; the position of the actual origin of the sound is uncertain (and this is frequently required), and again continuous variation of frequency is impossible.

Indirect acoustic generators.—An electrically operated piece of apparatus seemed far more promising than any other. As described elsewhere in the paper, means had already been obtained for the production of a constant-voltage supply of uniformly varying frequency, and it only remained to select a suitable form of instrument for the conversion of this into acoustic energy. A great many different types of instrument have been investigated, partly with a view to their use in such measurements as are described here, and partly for use as telephonic standards of transmission.

Piezo-electric devices.—The introduction of valve amplifiers renders possible the utilization of many effects which have been known for years but have so far been too minute for practical use. One of the most promising of these is the piezo-electric effect. Certain crystalline substances, of which Rochelle salt, quartz and tourmaline appear to be the most noteworthy, have the property of producing on portions of their surfaces an electric charge upon being mechanically compressed. The effect is completely reversible. There is a very considerable amount of literature on the subject, but there has not been much work published on its application to telephone problems.

A. McL. Nicholson * has given the results of his work in this connection, and has described the production of suitable Rochelle salt crystals. Rochelle salt gives by far the most powerful piezo effect of any substance so far known, and this was investigated by the authors. Excellent results were obtained at first, and transmitters were constructed with apparently very flat frequency characteristics, though no direct measurements were made. It was, however, found impossible to maintain constancy. The piezo effect is largely due to internal strain in the crystal, and with a fragile material like Rochelle salt, and one which is moreover affected by moisture, reliability could not be obtained. Quartz is mechanically an ideal substance, its drawback being its lack of sensitivity. It has recently been extensively used for wave-meters, as suggested originally by W. G. Cady.† The use of this material as both transmitter and receiver in conjunction with suitable amplifiers is now being investigated.

Electrostatic transmitters.—That a condenser having its plates not rigidly clamped would, when actuated electrically with an alternating voltage, produce a sound of twice the frequency was first pointed out, it is believed, by Dolezalek.

* *Journal of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 1467.
† *Proceedings of the Institute of Radio Engineers*, 1922, vol. 10, p. 83.

By polarizing the condenser with a battery the condenser will reproduce the input frequency, the effect being analogous to that occurring with non-polarized and polarized receivers. The use of condensers as transmitters and receivers has been known for a very long time, but on account of their lack of sensitivity it was only the advent of the thermionic valve which enabled a practical use to be made of them.

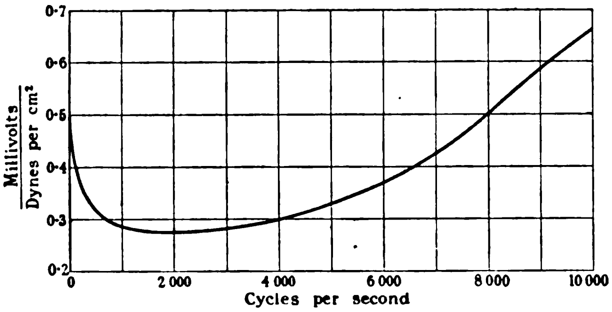


Fig. 1.—Calibration of electrostatic transmitter.

A full description, with the theory, of an instrument which has been developed by the Western Electric Company of America for use as a standard is given by E. C. Wente.* This instrument consists of a two-plate condenser, one plate, which receives the incoming sound, being a thin stretched diaphragm separated from the second plate, which is massive, by a small air-gap. Incoming sounds vary the capacity of this condenser and, by suitably designed filter and amplifier circuits, the effects are amplified for measurement.

A frequency characteristic of one of these instruments taken from the original paper is shown in Fig. 1. It has been used to a very considerable extent in America in a number of diverse investigations both in connection with telephone transmission and in more purely acoustic investigations. It is stated to be very reliable and stable.

This instrument has not been used by the authors, but a number of other forms of electrostatic transmitter have been examined. A loud-speaker can be produced from a few loose sheets of foil with paper or gutta-percha separators, but it has obvious disadvantages for the present purposes.

Another arrangement being investigated consists of a two-plate condenser, one plate being formed of a thin sheet of aluminium foil stretched just sufficiently taut to hold it plane and held a few thousandths of an inch away from a rigid back plate. This condenser forms part of a special circuit which is similar to that devised by J. J. Dowling for the measurement of minute lengths and termed by him the ultra-micrometer.* The circuit employed is shown in Fig. 2. It will be noted that the electrostatic transmitter is unpolarized and is connected to a pick-up coil of an oscillator which is arranged to oscillate at some convenient radio frequency (about 800 000 cycles has been found suitable in London).

The pick-up coil is connected to a detector valve and a 1- or 2-stage transformer-coupled audio-frequency amplifier, and thence to a measuring instrument, which may be a Moullin voltmeter. The oscillator is set to oscillate slightly out of tune with the circuit formed by the condenser transmitter and oscillator output coil, the amount of mistuning being shown by the ammeter in the detector plate circuit, a definite plate current being worked to. Sounds incoming to the transmitter modify the degree of tuning, with the result that the potential of the detector grid is modified accordingly.

This scheme is sensitive and promises to be of value, but has not yet been very fully investigated.

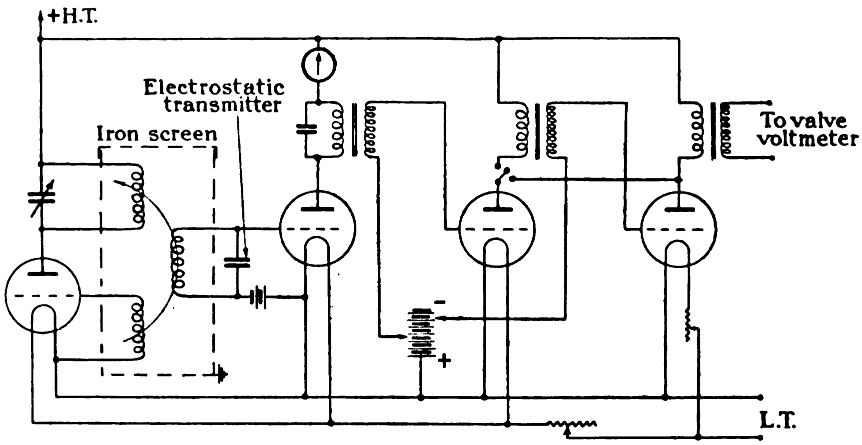


Fig. 2.—Sensitive electrostatic transmitter circuit.

Thermophones.—Of recent years numerous devices have been brought out for the conversion of acoustic into electric vibrations, and vice versa, based on the variation in resistance of a fine wire when subjected to acoustic vibrations. Commercial telephone instruments have been produced in Holland and Germany, and considerable use was made of similar apparatus in the late war. A thermophone, as this type of instrument is called, has been used in America as a means of standardizing the electrostatic transmitter.† A great deal of work has also been done by Major Tucker with hot-wire microphones for acoustic experiments.

There is much to be said for the use of thermophones

* *Physical Review*, 1917, vol. 10, p. 22, and 1922, vol. 19, p. 498.

* *Philosophical Magazine*, 1923, vol. 46, p. 81.
† H. D. Arnold and I. B. Crandall: *Physical Review*, 1917, vol. 10, p. 22; and E. C. Wente, *ibid.*, 1922, vol. 19, p. 333.

in acoustic measurements; they are small, cheap and, in some respects, simple in use. It is necessary, however, partly to obtain sensitivity, and partly to reproduce the impressed frequency and not double this, for the thermophones to be polarized with a direct current (analogous to the use of the polarizing magnet in an ordinary receiver). This polarizing current must be large in comparison with the alternating current in order to avoid second harmonics and to get the necessary sensitivity, and in practice the number of burn-outs is inconveniently large. The instrument must also be very carefully screened from draughts and mechanical vibration, and in addition the sensitivity also falls off with the frequency.

Thermionic devices.—The electronic discharge in air from a heated cathode can be directly operated upon by a sound wave which will vary the electron flow. This effect has been utilized in America and in Germany to produce a transmitter for broadcasting purposes. The great advantage of such an instrument is its freedom from resonance, and, if a reliable instrument could be made, it would be ideal for measurement purposes. A few preliminary experiments with the German type of instrument indicated, however, that considerable variability would be experienced and that, although the principle was simple enough, numerous protective devices, etc., were needed and greatly reduced its simplicity. The arrangement is not reversible.

Electromagnetic devices.—Apparatus based upon electromagnetic action appeared to offer the best prospect of producing an instrument satisfactory for the purpose required, and different types were examined. They have the great advantage over electrostatic instruments in that no trouble is experienced such as is found with condensers owing to the relatively small capacity of an electrostatic transmitter in comparison with the leads connecting it with its amplifier.

The ordinary electromagnetic receiver of commerce is a robust and sensitive instrument but has a very pronounced diaphragm resonance at about 1 000 cycles per sec., and usually others of a higher value as well. By reducing the air space at the back of the diaphragm the sharpness of this resonance can be reduced and its frequency considerably raised, and for many purposes this will make a very satisfactory sound source or pick-up device. Its efficiency at frequencies away from its resonant frequencies is, however, comparatively low.

The moving-coil type of instrument with either a flat or solenoidal coil operating in a strong annular magnetic field offers many possibilities. A loud-speaker on this principle has been described by Lodge,* and successful loud-speakers operating on this principle are in use to-day. The standard microphone adopted by the British Broadcasting Company is also of this type.

A number of instruments of this type, with a solenoidal moving-coil on a mica cylinder and working in a powerful annular magnetic field were made for a special purpose in 1915. Some of these, suitably modified to operate with inertia control, are being used as high-quality receivers and transmitters.

In the best form, the space behind the moving parts is kept open to the air to prevent acoustic loading, and the back of the instrument is at the same time enclosed in a padded box to prevent interaction between the back and the front. This interaction would otherwise be particularly noticeable at the lower frequencies.

Another type of instrument has been suggested by Siemens and Halske of Berlin and used, it is believed, in Germany for broadcasting and also as a loud-speaker. It consists of a strip of thin aluminium foil about 12 cm × 1 cm lightly clamped at the ends and placed in a strong magnetic field. Acoustic vibrations falling upon this strip will cause it to vibrate and generate an e.m.f. The reverse may also take place, viz. currents in the strip will cause it to vibrate and generate sound waves. The chief interest in the arrangement lies in the fact that if the strip be vibrating, due to impact

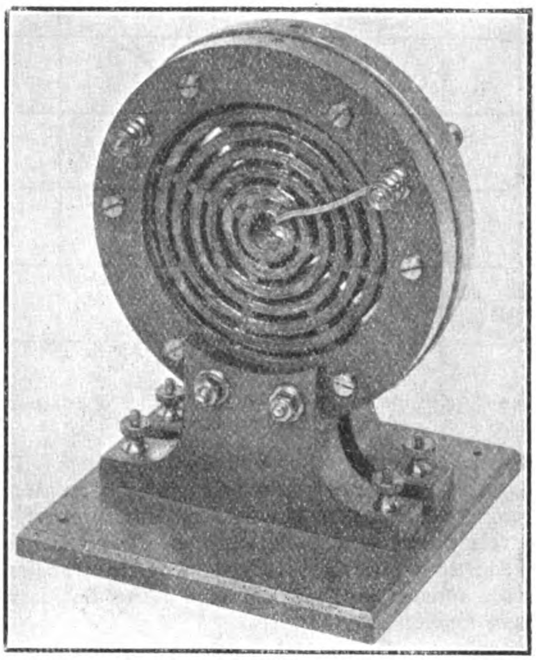


FIG. 3.—Eddy-current instrument.

of acoustic waves, it may be brought to rest by passing a current of correct amplitude and phase through it; this current will be some measure of the acoustic output.

The theory does not appear to have been completely worked out, the correction to be made for air leakage round the edges of the strip being rather uncertain.

Eddy-current instrument.—An instrument which has been found to be of great value is that known as a Hewlett tone generator. This is the name given the instrument by its inventor, C. W. Hewlett, but eddy-current transmitter or receiver would appear to be a more suitable name. A description of the instrument, with the theory of its action, and particulars of its performance are given in the *Physical Review* (1922, vol. 19, p. 52).

The construction of the instrument is as follows: Two pancake coils, each consisting of a number of concentric coils arranged with annular air spaces between, are fixed face to face about 50 mils apart. In the

* *Journal I.E.E.*, 1898, vol. 27, p. 799.

centre of this space is clamped a diaphragm of thin aluminium foil, stretched just sufficiently taut to keep it plane. In the two pancake coils a direct current is caused to flow in such a way as to produce opposing magnetic fields. The aluminium diaphragm is thus situated in a radial magnetic field. If, now, a sound wave falls upon the diaphragm and sets it in vibration, eddy currents will be induced in it and will, in turn,

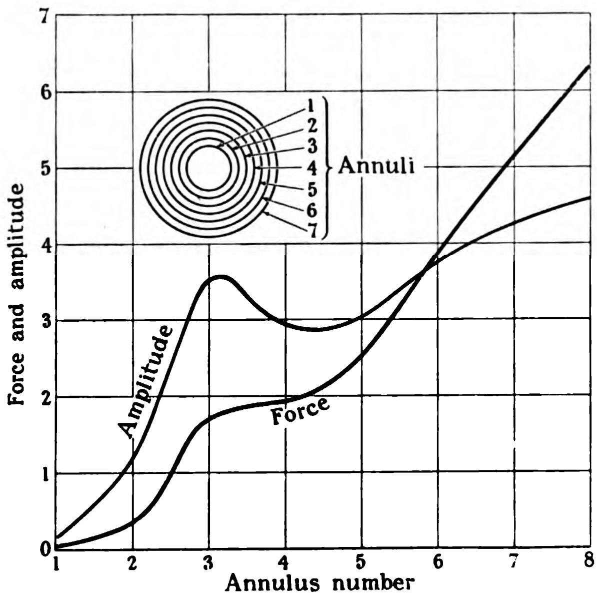


FIG. 4.—Amplitude of motion of, and force on, diaphragm of eddy-current instrument.

induce voltages in the pancake windings. These voltages can be tapped and utilized as a measure of the sound vibrations. There is no iron present, and from this cause, and the nature of the construction, the acoustic-electric and electric-acoustic transformations are remarkably pure. Fig. 3 shows one form of the instrument.

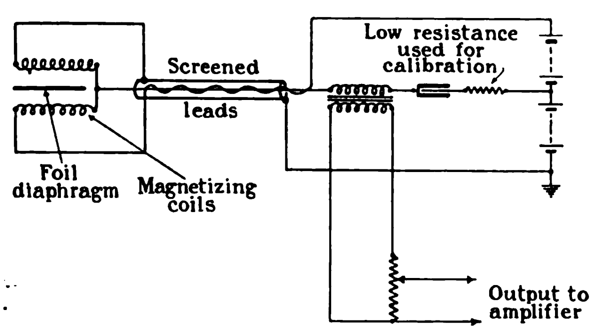


FIG. 5.—Eddy-current instrument circuit.

Hewlett has made measurements and calculations of his original instrument and found them to be in close agreement, the instrument being used as a source of sound. Fig. 4 shows the relationship between the amplitude of motion of, and also the force acting upon, each annulus of the diaphragm, annulus No. 1 being that near the centre. It will be seen, therefore, that the maximum motions, unlike those in most vibrating diaphragms, occur near the edge, and that the centre is practically at rest. The forces acting upon the different annuli are nearly in phase, so that the diaphragm is vibrating as a whole. Hewlett shows that, when used as a sound generator for voice frequencies, the force acting upon the diaphragm is directly proportional to the frequency, and the amplitude of vibration is inversely proportional to the frequency.

The first transmitter made for the authors was in accordance with Hewlett's design, in which the same coils are used to polarize the instrument as for picking up the E.M.F.'s induced from the diaphragm currents. The circuit of the instrument is shown in Fig. 5. Another form has been designed in the Post Office Research Laboratories. In this model separate polarizing and output windings are used. By making the output winding with a large number of turns the instrument can be caused to operate efficiently directly upon the grid of the first amplifier valve, thus eliminating the iron-cored input transformer shown in Fig. 5. The separation of the two windings also renders the circuit arrangements more flexible. From two to five stages of amplification are required with eddy-current transmitters.

All leads from the transmitter must be screened, and the transmitter itself is placed within a cage of heavy copper wires. This is mainly required to prevent direct electric and magnetic induction from the electrically operated sound source to the transmitter.

METHOD OF CALIBRATING ACOUSTIC MEASURING INSTRUMENTS.

Although according to Hewlett the operation of the instrument is calculable, it was thought that a direct measurement of its performance would be more satisfactory.

The calibration, which is, of course, applicable to other types of instrument when used as a transmitter, was made by means of a Rayleigh disc. A description of the Rayleigh disc instrument, and the method of calibrating it by means of a continuous flow of air, have recently been published by E. Mallett and G. F. Dutton in the *Journal* * and need not be repeated in detail. Calibrations were made with air flowing in both directions past the disc, and, to ensure uniform flow of air, each end of the calibrating tube was filled with a bundle of small tubes, each about 3 in. long by $\frac{1}{8}$ in. bore.

Mallett and Dutton, in the same publication, showed that a chamber lined with 4 in. of cotton waste on each wall was practically non-reflecting, and a similar arrangement was used by the authors. The Rayleigh disc used consisted of a thin piece of mica 0·75 cm in diameter and carrying a small mirror at its centre; it was suspended approximately in the centre of the chamber, which was 4 ft. each way and lined with the cotton waste.

The eddy-current transmitter was suspended, with diaphragm vertical, about 6 in. behind the disc, and with the centre of the diaphragm in the same horizontal plane as the centre of the disc. Fixed in the side of the chamber, also in the same horizontal plane, was a brass tube in which could be made to slide a telephone

* *Journal I.E.E.*, 1925, vol. 63, p. 502.

receiver used as a source of sound. The brass tube itself could also be moved in and out in order to bring its mouth within varying distances of the disc and eddy-current transmitter, these two remaining fixed.

The adjustable air column in front of the receiver was used, as by Mallett and Dutton, to reinforce and purify the sound. The range of frequency which can be covered in this way is, however, limited. It was extended up to 3 000 cycles by fitting an adjustable perforated cap immediately in front of the diaphragm, thus providing a small air chamber which served as a Helmholtz resonator. A value at about 4 000 cycles was obtained by utilizing the nodal circle resonance of the diaphragm. The heterodyne oscillator, described elsewhere in the paper, energized the telephone receiver used as a source of sound.

Preliminary tests were made at frequencies of 1 000 cycles and 3 500 cycles by means of a loose receiver inside the chamber, and these confirmed Mallett and Dutton's results that the wave-front a few centimetres in front of the receiver is spherical; also that this is not perceptibly affected by the presence of the eddy-current transmitter.

TABLE 2.

Frequency	r_2 cm	E	r_2E	Frequency	r_2 cm	E	r_2E
310	23	0·72	16·6	2 910	22·1	4·12	91
	24·7	0·68	16·8		23	3·85	88
	26·5	0·62	16·4		23·9	3·74	89
					24·7	3·68	91
					25·6	3·45	89
					26·5	3·40	90
					27·4	3·4	93
					28·3	3·34	94
Mean	..	..	16·6	..	..	..	90·6

A series of voltmeter readings were taken from the amplifier at several different frequencies for various distances between the source of sound and transmitter. Two of these are shown in Table 2, together with the value of the product r_2E, r_2 being the distance between the centres of the source and the diaphragm. It will be seen that r_2E is a constant.

Mallet and Dutton have shown that for a spherical wave the R.M.S. pressure p at a distance r_2 from the source is given by

$$pr_2 = \frac{A\rho\omega}{4\pi\sqrt{2}}$$

where A = a constant, ρ = air density, and $\omega = 2\pi \times$ frequency.

It follows, therefore, that at a given frequency the voltage indicated from the transmitter is proportional to the pressure of the sound wave.

Frequency characteristic of the transmitter.—This is obtained by simultaneous measurements made of the deflections of the Rayleigh disc and the transmitter voltage.

The deflection of the disc is proportional to the square of the velocity v of the air particles, the relation being obtained by a measurement of the deflection for various steady currents of air, as previously explained.

With the disc and suspension used it was found that if δ be the deflection

$$v = 0\cdot153\sqrt{\delta} \text{ cm per sec.}$$

With a spherical wave

$$v = \frac{A}{4\pi\sqrt{2}}\sqrt{\left(\frac{1}{r_1^2}\cdot\frac{\omega^2}{c^2} + \frac{1}{r_1^4}\right)}$$

where A = a constant, as above,
r_1 = distance between disc and source,
c = velocity of propagation of sound,
$\omega = 2\pi \times$ frequency.

As previously stated, if p is the pressure at the transmitter diaphragm situated r_2 cm from the source

$$p = \frac{A\rho\omega}{4\pi r_2\sqrt{2}}$$

$$\therefore p = \frac{v\rho\omega}{r_2\sqrt{\left(\frac{1}{r_1^2}\cdot\frac{\omega^2}{c^2} + \frac{1}{r_1^4}\right)}}$$

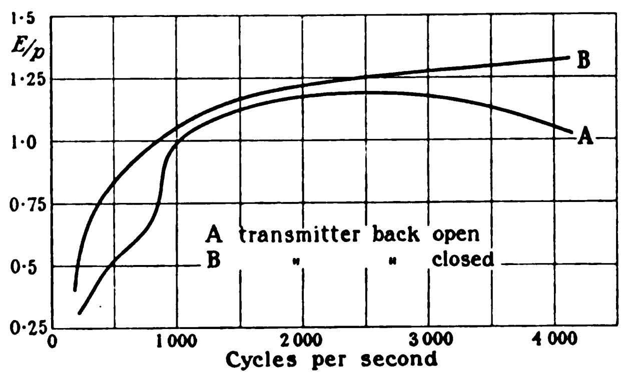


FIG. 6.—Calibration of eddy-current transmitter.

This value of p was obtained for different frequencies, together with the corresponding values of E. Since, as previously stated, it had been found that p is proportional to E, the potential difference from the transmitter, E/p will be the output voltage for a constant pressure. This is plotted in Fig. 6 against the frequency.

At each frequency several values of r_1 and r_2 were taken. It was found that E/p was not always quite constant, due to the fact that as r_2 became great enough at the higher frequencies a certain amount of reflection was found. Its effect could, however, always be allowed for.

It will be seen the transmitter output rises steadily to about 1 000 cycles, after which it is substantially constant.

The characteristic is considerably improved by enclosing the back of the instrument by sound-absorbing material (see curve B). A similar result is obtained by putting a baffle plate round the diaphragm.

Apparatus for the Production of Electrical Energy of Constant Value over the Required Range of Frequency.

Before the introduction of thermionic oscillators recourse was had to alternators, interrupters and electromagnetic vibratory apparatus for the production of audio-frequency alternating currents. Reference will be made to some of these.

Alternators.—A number of alternators have been specially designed to produce pure wave-form alternating current at audio frequency. Reference may be made to the machines of Duddell, Franke, Pollock and Brown. The alternator of Duddell gives alternating current of good wave-form up to 2 000 cycles. The machine has to be driven at a speed of 8 000 r.p.m. to give this frequency. The Pollock alternator gives up to 6 000 cycles at 6 000 r.p.m.

Microphone hummers utilizing the interaction between a microphone and an electromagnet to maintain a reed, bar, or tuning fork in vibration are widely in use for measurements at one frequency.

All the devices so far referred to, with the exception of alternators, are of no value for the production of alternating current which can be varied continuously over the required range of frequency.

The thermionic oscillator can, however, be arranged to cover all the requirements.

Thermionic oscillators.—The production of an ordinary type oscillator, giving a pure wave-form and constant output, with a frequency continuously variable over the audio range, is extremely difficult, even if possible. During some preliminary work on a means of obtaining a range of sinusoidal frequencies, the use of two ultra-audio oscillators heterodyning with one another was

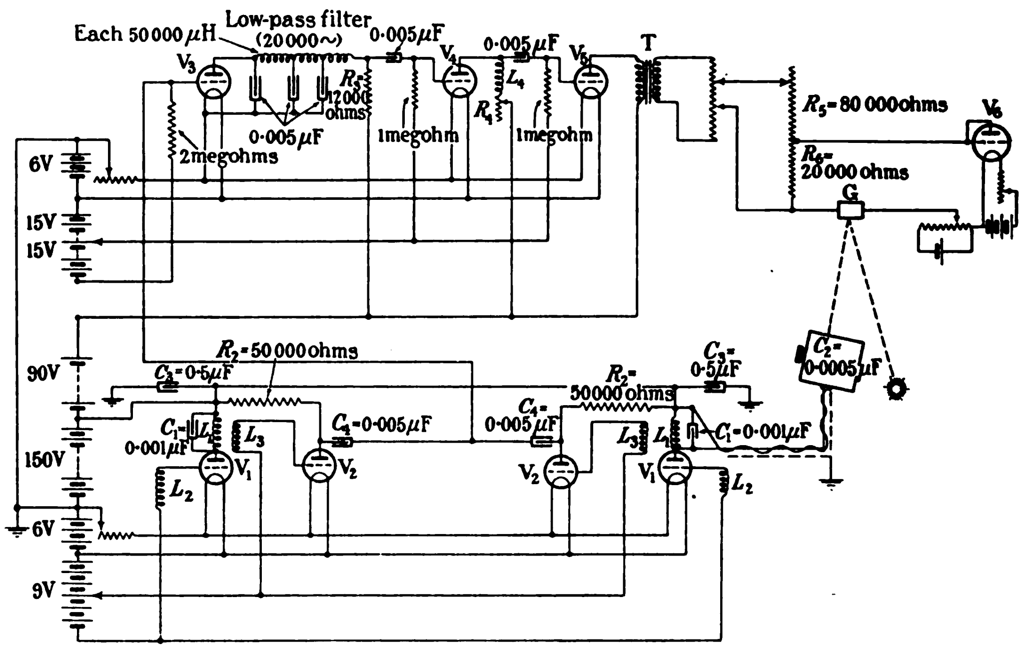


Fig. 7.—Complete circuit of heterodyne oscillator.

These instruments are particularly useful when very considerable output is required.

Interrupters.—Vibrating wires operated electromagnetically and with mercury-cup interrupters have been used for the production of audio-frequency alternating currents. By the addition of tuned circuits, trains of oscillations were obtained on make or on break, and were also combined on both make and break to give a more or less continuous wave.*

Interrupter commutators consisting of a series of segments regularly graduated in width have been used to produce alternating currents rhythmically varying over a desired range of audio frequency, and this apparatus is still in use for certain testing purposes.†

tried with promising results, and this appeared to be a method which could be usefully applied to the present problem.

If an oscillator working at a frequency of, say, 25 000 cycles per sec. is coupled loosely with another which is caused to oscillate at any point between 25 000 and 30 000 cycles, the fundamental of each oscillator will be inaudible, but a "beat" frequency will be introduced varying between 0 and 5 000 cycles. No difficulty is experienced in obtaining the "beat" frequency, but considerable difficulties are encountered in rendering it sinusoidal in shape and constant in value, and it is essential to secure these qualities if the maximum use and convenience are to be obtained from the instrument.

At frequencies of 25 000 cycles a change of frequency of 5 000 cycles can be effected by changing the oscillator capacity by a small amount, which car be covered in

* B. S. Cohen: "The Production of Small Variable-Frequency Alternating Currents suitable for Telephonic Measurements," *Philosophical Magazine*, 1908, vol. 16, p. 480.

† B. S. Cohen: "Telephonometry", *Institution of Post Office Electrical Engineers*, Paper No. 70, 1916.

a 180° movement of a small air condenser. This means that the whole range of audio frequencies normally required (say 0 to 5 000 cycles) can be obtained by the rotation through 180° of a single dial. The range can, of course, be altered by modifying the ultra-audio oscillators, or the small variable condenser.

The general method of operation is to cause the oscillator to actuate the apparatus under investigation, the result of this actuation being measured as a galvanometer deflection recorded photographically on paper on a drum which is rotated with the variable air condenser used to obtain the variation in frequency. This method of operation required the use of receivers or transmitters having equal outputs over the range of frequencies under consideration. For example, in examining a transmitter for resonance it would be actuated by a special non-resonant receiver operated from the oscillator, and the a.c. output would be rectified and passed through a d.c. galvanometer, the deflections of which would be recorded, as described above. A receiver would be tested by operating it from the oscillator, and causing it to actuate a non-resonant transmitter. Non-acoustic apparatus such as transformers, induction coils, etc., are examined by current or voltage measurements.

In designing the apparatus at present in use the following requirements have been covered :—

(1) The range of audio frequencies covered by the rotation of the dial of the operating variable condenser through 180° is from 0 to 5 000 cycles.

(2) The output at all frequencies within the range is practically sinusoidal.

(3) The output voltage is practically constant for all frequencies within the range.

(4) The high frequencies of the oscillators are eliminated before reaching the audio-frequency output, in order to prevent interference with current measurements on the galvanometer.

Heterodyne oscillator circuit.—The circuit diagram of the heterodyne oscillator used by the authors is shown in Fig. 7, which illustrates also the method employed for taking photographic records. Each high-frequency oscillator circuit comprises a grid coil L_2 of 50 000 μH, coupled to a plate coil L_1 of 20 000 μH, tuned by a fixed condenser C_1 (about 0·001 μF). A variable condenser C_2 with a maximum value of 0·0005 μF is connected in parallel with one of the condensers C_1, to cover a frequency range of about 5 000 cycles. Output coils L_3 of 10 000 μH introduce the high frequencies from each oscillator into the high-frequency amplifying valves V_2, which serve to prevent, as far as possible, interaction between the two oscillators ; each oscillator, with its associated high-frequency amplifier, is also enclosed in an iron box. The high frequencies are taken by resistance-capacity coupling and a common input lead to the grid of the detector valve V_3, which operates on the anode rectification principle. In the plate circuit of this valve is a low-pass filter having a cut-off at about 20 000 cycles ; the filter serves to reduce to a negligible quantity the high frequencies in the audio-frequency output ; moreover it provides, for the high frequencies, a sufficiently low-impedance path from the plate to the filament to ensure efficient operation of the detector valve. Two stages of resistance-capacity coupling bring the audio frequencies to the output transformer of the set.

Output/frequency characteristic.—With an ordinary-type output transformer, the output/frequency characteristic was found to be unsatisfactory, the output increasing too slowly as the frequency was raised from zero, and falling off again at the higher frequencies. Output transformers for the heterodyne oscillator are

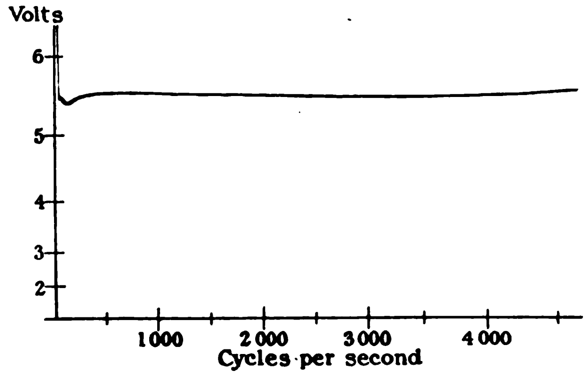


FIG. 8.—Heterodyne oscillator voltage/frequency characteristic.

accordingly built on 1-in. square cores of stalloy stampings, the windings consisting of a number of interleaved wave-wound slab coils. It is, of course, essential that the secondary winding should terminate with a non-reactive load, a generally useful value for which has been found to be 800 ohms, through which a current of about 10 mA is obtainable. When more current is required this load may be increased to, say, 100 ohms,

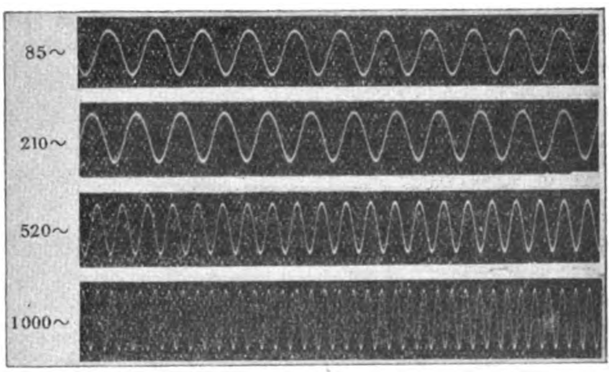


FIG. 9.—Wave-forms of heterodyne oscillator.

and the transformer ratio and resistance of the secondary winding may conveniently be adjusted by joining in parallel certain of the slab coils.

Whilst such a transformer gives a satisfactory output at the low frequencies, there is a tendency for the output to fall off at the higher frequencies. In order, therefore, to flatten out the characteristic, the output at the lower frequencies is cut down to the same value as that obtainable at the high frequencies. To effect this, a 0·2 henry air-cored inductance L_4 was inserted in the anode circuit of the first audio amplifying valve in series

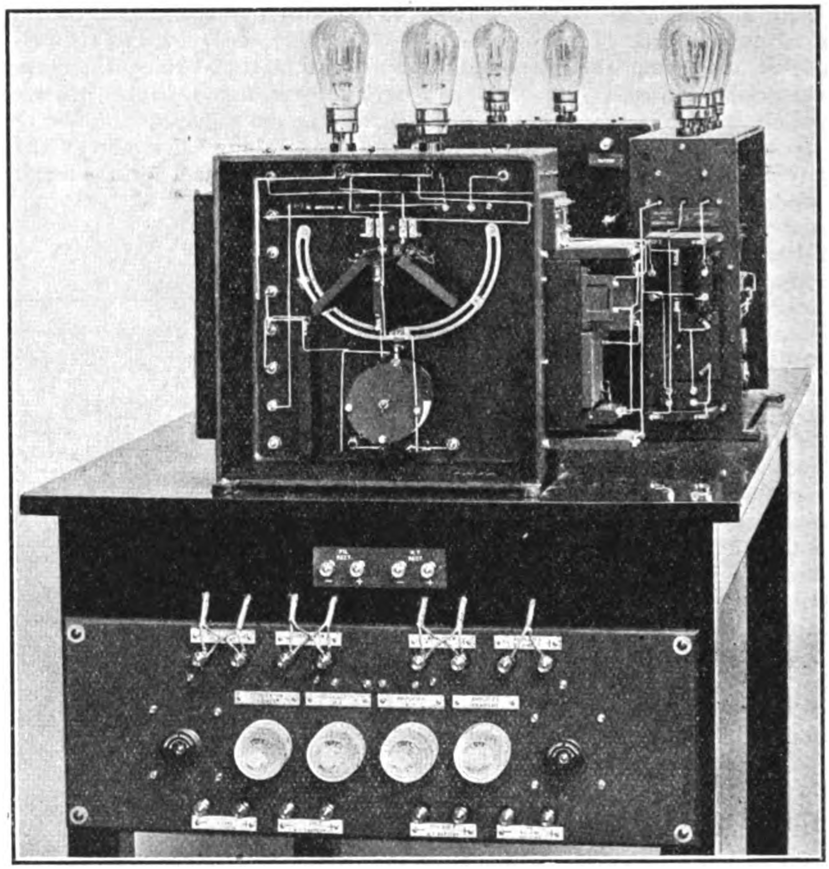


FIG. 10.—General view of heterodyne oscillator.

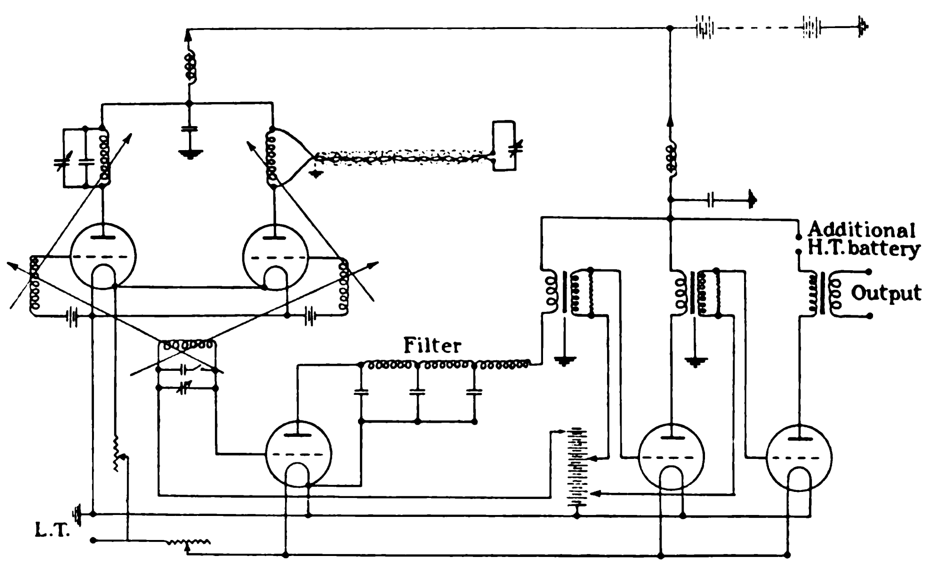


FIG. 11.—Circuit diagram of portable heterodyne oscillator.

with a variable non-inductive resistance R_4, the impedance of this circuit thus having a rising characteristic with frequency. A photographic record of the output/frequency characteristic of the oscillator is reproduced in Fig. 8.

The method of measurement is illustrated in Fig. 7. A rectifying valve V_6 has in circuit a quick-moving reflecting galvanometer G, the spot of light from which falls on photographic paper wound round the drum of the condenser camera C_2. In the illustration V_6 is shown as a diode rectifier. As a general rule, however, it is preferred to use a triode with anode rectification.

For many purposes it is convenient to substitute for the condenser camera a pair of variable condensers in parallel, one of say one-half the capacity of the other, and one equipped with a vernier. This vernier can be adjusted so that the beat frequency is zero when both condensers are set at zero. One condenser will then give half the available frequency range of the oscillator for a 180° rotation of its dial, whilst the whole frequency

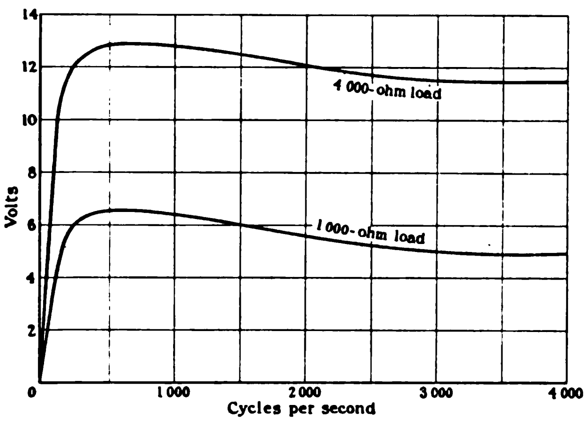


FIG. 12.—Voltage/frequency characteristics of portable heterodyne oscillator.

range is obtainable from the other condenser. The dials of both condensers may be engraved in frequencies.

Wave-form.—Oscillograms showing the wave-form of the output at different frequencies are reproduced in Fig. 9, the frequencies being 85 cycles, 210 cycles, 520 cycles and 1 000 cycles. The impurity is almost entirely due to a second harmonic, as was tested by tuning out first the fundamental and then the second harmonic. From a measurement, with the impure wave-form, of the capacity of a condenser, the impurity was found to be less than 5 per cent of the fundamental.

A variable condenser (about $0 \cdot 001\ \mu F$ maximum) shunted across the input to the detector valve has been found to be a useful addition to the heterodyne oscillator. As the value of this capacity is increased, so the output from the oscillator is reduced and, at the same time, the wave-form is improved. Hence, whenever the maximum output from the oscillator is not required, a suitable adjustment of this capacity is made in order to obtain the best wave-form available. The operation of the condenser in this respect is two-fold, by reducing the magnitudes of the alternating voltages in the audio-frequency amplifier it lessens the percentage of harmonics generated therein, and by providing, in the plate circuits of the high-frequency amplifying valves, an impedance, which is lower for the harmonics than for the fundamental, it tends to purify the wave-form of the high frequencies introduced into the detector valve.

Method of use.—The general method preferred for making frequency characteristic tests with the heterodyne oscillators is to introduce a constant voltage from the oscillator across a non-reactive resistance, which forms a part of the normal input connections to the apparatus under test, and to record the voltage output, with the circuit terminated by an impedance equivalent to that used under working conditions. This method involves the use of a suitable non-reactive attenuator, placed between the output transformer of the oscillator and the apparatus under test. This will serve to maintain a non-reactive load on the transformer and also to retain the normal impedance, on the input side of the apparatus under test, uninfluenced by the presence of the transformer.

Fig. 10 shows one of the ultra-audio oscillators.

Portable heterodyne oscillator.—A smaller and more portable pattern of heterodyne oscillator has also been constructed. The arrangement is somewhat different from that of the large instrument, and the circuit is shown in Fig. 11. It will be observed that no high-frequency amplifier stages are used in conjunction with the oscillators.

Fig. 12 shows frequency characteristic curves for two outputs of this instrument.

THE FREQUENCY CHARACTERISTICS OF TELEPHONE TRANSMITTERS.

The most suitable sound source available for operating the transmitters was a receiver of the moving-coil type mentioned on page 1027. The output of sound from this instrument was ascertained indirectly by using an electrostatic transmitter, working on the circuit shown in Fig. 2 and calibrated by means of the Rayleigh disc; and also, for frequencies up to 1 500 cycles, by direct measurements on the Rayleigh disc. At frequencies higher than about 1 500 cycles the sound velocities were too low to be accurately recorded by the disc. The two records of sound output so obtained were found to be in very close agreement, and on these are based the sound-input curves to the transmitter, which are shown in Figs. 13 (*a*) and 14 (*a*). These values of sound input represent what would be the pressure of the sound wave at the position of the aperture of the transmitter if the latter were removed. That is to say, no account is taken of local irregularities in the sound wave due to the presence of the transmitter.

The transmitter was fed with about 40 milliamperes of direct current through a transformer and a resistance of 300 ohms, and the alternating E.M.F. generated by the sound was amplified, rectified and photographically recorded. Sound source and transmitter were placed for the test in the previously described acoustic chamber.

The records shown can only be accepted as indicating the order of performance, owing to the fact that ordinary granular transmitters when operated upon by a constant sound input tend to "pack." A record taken with a rising frequency is usually somewhat different from that

taken with a falling frequency. The resonant frequencies also seem to differ to some extent both in relative amplitude and in frequency when taken at different times.

Fig. 13 (*a*) shows the characteristic of an "inset" transmitter of the type used in this country on local-battery instruments. This instrument has a small carbon diaphragm, and considerable damping is introduced by the large chamber, three-quarters full of

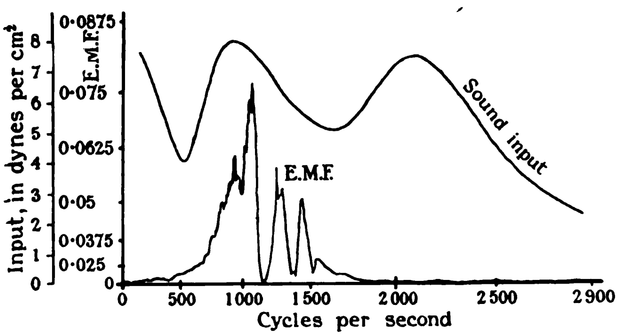


FIG. 13 (*a*).—Characteristic of local-battery transmitter with mouthpiece.

granules held in place by cotton wool cemented to the diaphragm. The record is typical, but considerable variation occurs between different specimens. This instrument is particularly susceptible to "packing" under the conditions of the test.

Fig. 13 (*b*) shows the characteristic of a granular transmitter specially designed to give good articulation. It has a 40-mil carbon diaphragm separated from a massive back plate by an air space of 7 mils. The granules are held in a small central chamber in a felt

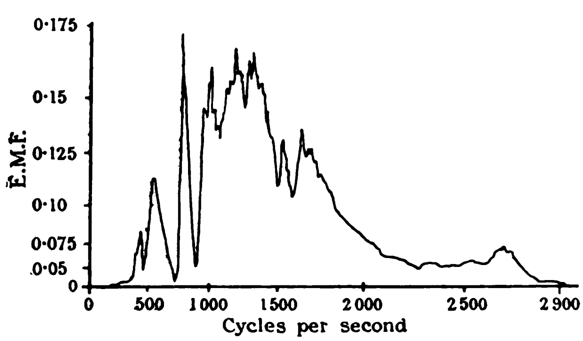


FIG. 13 (*b*).—Characteristic of special transmitter.

ring lightly resting against the diaphragm. This latter is open to the speaker, no mouthpiece being used. It will be seen that the characteristic is much more uniform. The articulation of this transmitter is of a very high order.

Fig. 14 (*a*) shows the characteristic of a standard-type common-battery transmitter with mouthpiece. This type of instrument, which possesses much greater uniformity in volume output than the local-battery pattern, is a somewhat complicated structure. It contains a small central chamber holding the granules. The back electrode is fixed. The front one is held in place by a thin annular mica diaphragm which, with its associated loads, has a natural frequency of the order of 1 200 cycles. Rigidly clamped to this front electrode is the larger aluminium diaphragm which receives the sounds. This diaphragm is not clamped at the circumference, but is encased there in a rubber ring and held down on its seating by two stiff, steel, felt-padded springs, one bearing on the diaphragm near the centre and the other near the edge. It will be

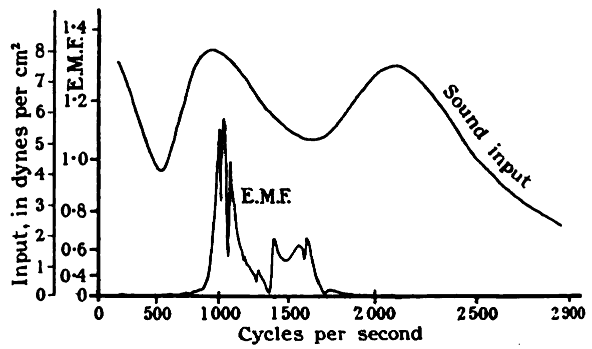


FIG. 14 (*a*).—Characteristic of common-battery transmitter with mouthpiece.

seen that a complicated series of mechanical resonances are possible. These transmitters usually show pronounced resonance between 900 and 1 500 cycles, but this often takes the form of two or more adjacent peaks.

There is also an acoustic resonance of the air in the chamber in front of the diaphragm and in the mouthpiece. This takes the form of a blunt, irregular peak,

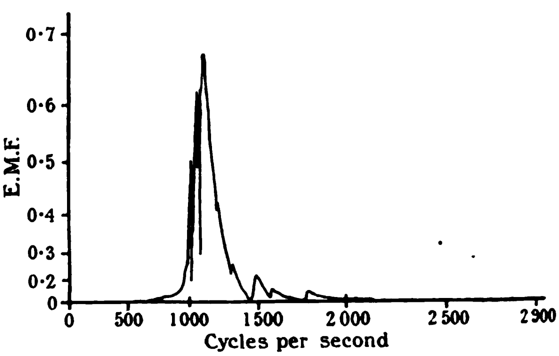


FIG. 14 (*b*).—Characteristic of common-battery transmitter without mouthpiece.

between 1 500 and 2 000 cycles, and smaller than that of the main mechanical resonance. When the mouthpiece is removed the acoustic resonance peak appears at about 2 900 cycles, but it is small and cannot usually be detected unless the curve is taken on a magnified scale. With this exception, therefore, it is considered probable that the peaks shown on the transmitter curves, when taken without a mouthpiece, are entirely due to mechanical resonances of the vibrating parts.

Fig. 14 (*b*) shows the characteristic of the same transmitter without mouthpiece.

THE FREQUENCY CHARACTERISTICS OF TELEPHONE RECEIVERS.

Under working conditions the receiver is held to the ear, and its performance is thereby modified as compared with the condition when it is exposed freely to the air.

Table 3 shows the effect upon the main resonant frequency of the acoustic loading introduced when the receiver is held against the head.

TABLE 3.

Receiver number	Fundamental diaphragm resonance	
	With earcap aperture free	With earcap against ear
1	960	1 180
2	960	1 180
3	1 000	1 260
4	960	1 180
5	890	1 120
6	890	1 190

The average free diaphragm resonance is 943 cycles and average loaded resonance 1 185 cycles.

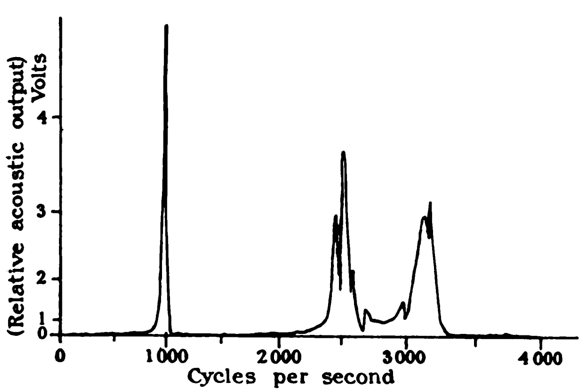


FIG. 15.—Characteristic of Bell receiver with earcap normal.

[This has an important bearing upon the method of using basic standard receivers. A small change in the position of the receiver may appreciably alter its characteristics. The most stable condition for the use of such a standard is with the diaphragm free to the atmosphere. For example, a guard ring may be fixed to the receiver earcap so that the ear is always at a definite distance.]

Interesting results as to the nature and positions of the mechanical resonances of the diaphragm are given by the sand figure method,* which shows that within the frequency range 0 to 4 500 cycles the diaphragm can vibrate in four different modes, namely the fundamental, the single-line mode, the two-lines mode and the single-circle mode. Owing to the central position of the pole-pieces, however, the response at the two intermediate modes is relatively feeble.

Using a Bell receiver, operated from the substantially constant output of the heterodyne oscillator, to actuate the eddy-current transmitter, the authors have obtained photographic records of the characteristics of telephone receivers.

Fig. 15 shows the frequency characteristic of a Bell telephone receiver placed at a distance of 17 cm from the diaphragm of the eddy-current transmitter. By using the calibration curve A of Fig. 6, the voltage output can be converted into sound pressures at the transmitter diaphragm at any desired frequency where the output is measurable.

Fig. 16 shows the performance of the same receiver, similarly placed, but with the earcap replaced by one which had been cut away to the clamping surface of the diaphragm. Sand figures observed with the receiver in this condition showed the fundamental at 970 cycles, the single-line mode at 1 660 cycles, the two-lines mode at 2 250 cycles—the response at this frequency was of sufficient strength to record in Fig. 16—and the nodal circle mode at 2 900 cycles per sec. These two curves show that the presence of the earcap introduces on the diaphragm an acoustic load which, even apart from the addition of an acoustic resonance, appreciably alters the characteristic.

All the records so far obtained for Bell receivers show

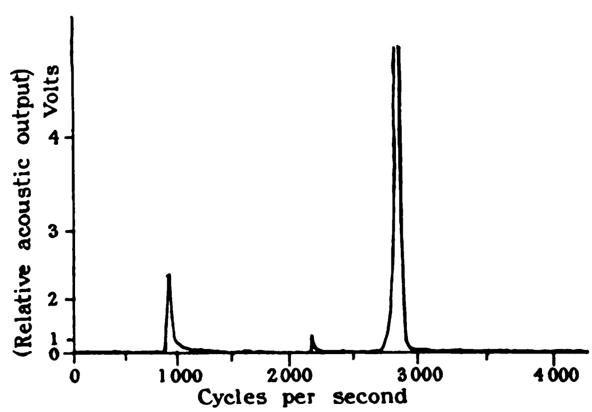


FIG. 16.—Characteristic of Bell receiver with earcap cut away.

three outstanding resonance peaks within the frequency range. Of these, the one at the lowest frequency, namely about 1 000 cycles, is that of the diaphragm vibrating at its fundamental mode. That at the highest frequency, usually 3 000 to 3 500 cycles, is due to the diaphragm vibrating at its single-circle mode. The intermediate peak occurs usually between 2 500 and 3 000 cycles per sec., is of less regular form and is caused by the acoustic resonance of the air chamber in front of the diaphragm. The two-lines mode of vibration may nearly coincide with this intermediate resonance but its response is comparatively small, as to a greater extent is the response at all other frequencies not in the vicinity of any of the three resonant peaks.

FREQUENCY CHARACTERISTICS OF TELEPHONE RECEIVERS MEASURED BY AURAL BALANCING.

It is of interest to investigate the frequency characteristics of receivers directly by the ear, and various

* J. T. MACGREGOR-MORRIS and E. MALLETT: *Journal I.E.E.*, 1923, vol. 61, p. 1134.

methods have been used for this purpose. The method so far found to give the most accurate results makes use, for balancing, of a fixed constant-frequency voltage which is applied to the receiver under investigation, the voltage being such as to give a suitable acoustic output.

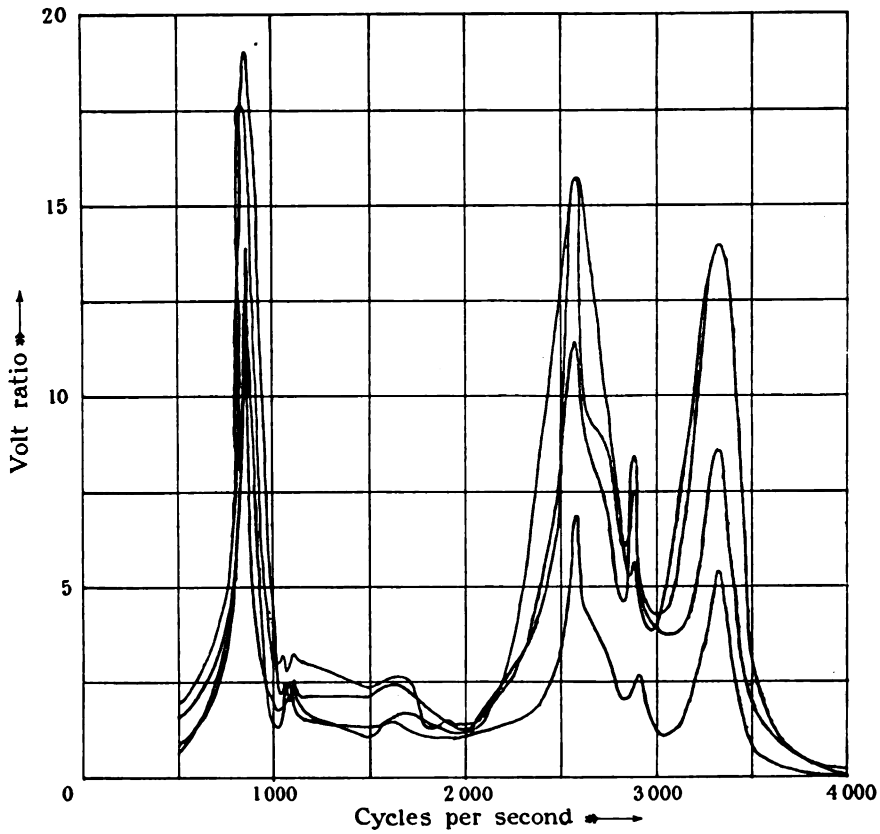


Fig. 17.—Characteristics of Bell receiver by aural balancing (4 observers).

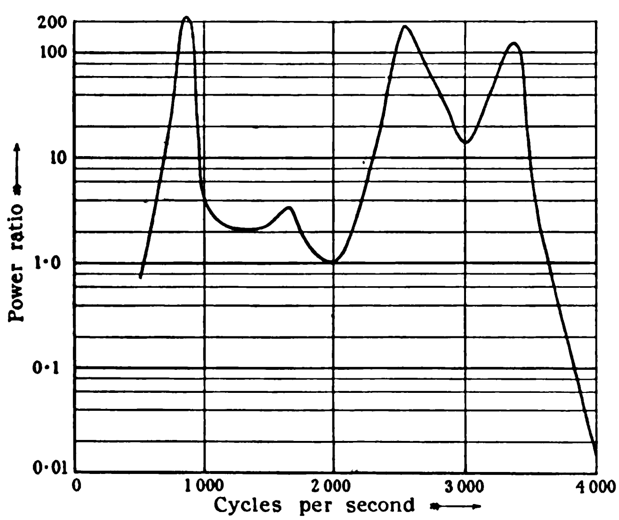


Fig. 18.—Frequency/power characteristic of Bell receiver by aural balancing.

The observer alternately applies to the receiver a voltage of this balancing frequency and of the particular frequency under comparison, the voltage of the latter being varied until the two sounds appear, to the ear, equal in volume. Although the frequency difference makes the balance more difficult, the method is capable of giving reasonably consistent results, as will be seen from the curves in Fig. 17, which gives the results for a particular 60-ohm Bell receiver. Tests were made by four observers, and using a balancing tone of 2 000 cycles. The receiver was tested at a distance of 1·5 in. from the ear.

The frequency responses, for convenience of measurement, are expressed as the ratios of the voltages of the two frequencies when balanced. The average result converted to ratios of power dissipated in the receiver is plotted in Fig. 18. This curve should be compared with Fig. 15, which shows the output characteristic as obtained by means of the eddy-current transmitter.

Receiver Diaphragm Movements.

Various methods of observing and measuring the motions of a receiver diaphragm have been described. Reference may be made to Wien, Shaw, Abraham, Duddell, Kennelly, Irwin and Kranz. The last-mentioned observer uses both vibrating mirrors and direct observation of a quartz fibre under the microscope.*

A modification of Kranz's methods has been experimented with and will now be described. Preliminary

* *Physical Review*, 1923, vol. 21, p. 573.

experiments were made using indicators attached to the diaphragm with sealing wax. These indicators consisted of small blown-glass cones or pieces of straw about 1 in. long, one end of which (the base in the case of glass cones) was attached to the diaphragm and the other end carried a small piece of microscope cover-glass. The glass was covered with acetylene soot and sprayed with mercury globules by means of an aerograph. Globules could be produced only a few microns in diameter and, when viewed by reflected light under the microscope, at a magnification of the order of 1 000 diameters, appeared as small stars on a dark background.

By flooding these cover glasses with Canada balsam in benzole, the mercury globules were firmly embedded and indefinitely preserved from tarnishing. The weights of the complete indicators varied between 13 and 40 milligrams, and it was found that a load of 40 milligrams attached to the centre of an ordinary receiver diaphragm weighing 3 227 milligrams had only a slight effect on the amplitude and frequency response for the fundamental diaphragm resonance. Indicators of this type enable the diaphragm motions, which are in the plane of the microscope field, to be measured by means of a micrometer eyepiece. When the motions are at right angles to the microscope field, the reflected points of light become, of course, blurs, but with a calibrated fine adjustment to the microscope these motions can also be measured. When any motions, other than normal to the diaphragm, occur, they will be due to angular motions of the attached indicator due to the bending of the diaphragm, and may occur at any mode of vibration other than the fundamental. The length of the indicator being known, the angle of bending can be obtained, provided the movement is brought within the plane of the microscope field. The effect on the diaphragm due to the stiffening over the area covered by the base of the indicator has so far been undetermined and may be considerable at the higher modes of vibration, and, until further examination, the results at the fundamental frequency only are dealt with.

By fixing the receiver to an electromagnetically operated reed vibrating a few times per second and at right angles to the normal diaphragm motion, the apparatus has been used to investigate transient diaphragm motions such as the clicks set up by condenser discharges and so on.

Bifilar vibrating indicator.—The following method has also been used for the examination of the diaphragm motion. A small hard-wood indicator is supported by bifilar suspenders of fine tungsten wire tightly stretched; it carries at one end a cover glass prepared as previously described. The other end of the indicator can be brought into contact with any point on a receiver diaphragm by suitable screw adjustments which move the receiver in two dimensions.

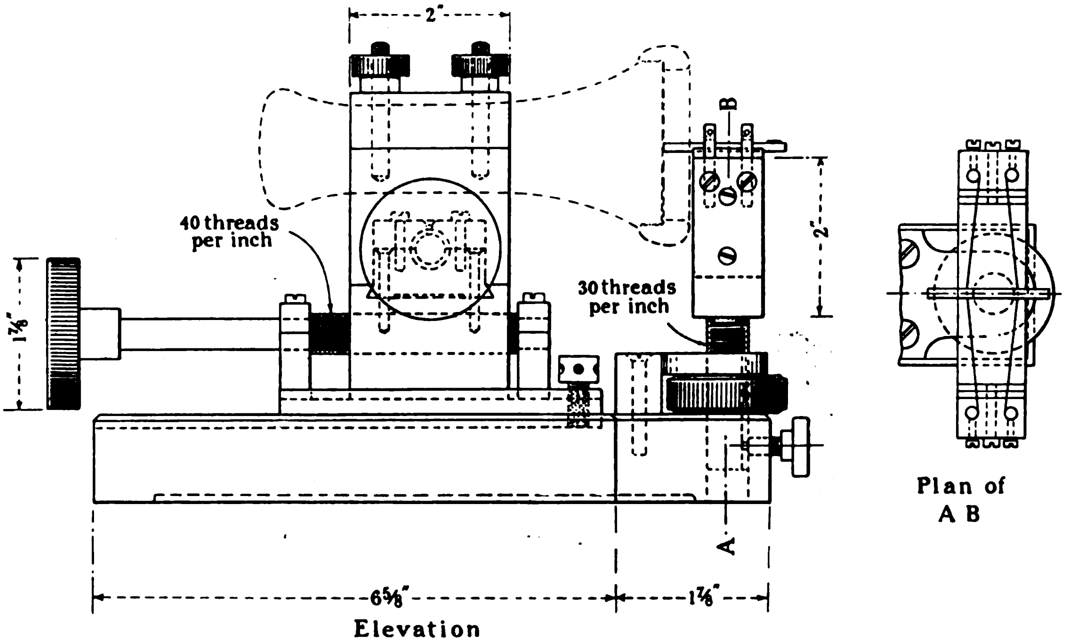


FIG. 19.—Diagram of bifilar instrument to measure diaphragm motion.

By calibrating, in terms of the pressure in milligrams, the steady deflections of the indicator when the diaphragm is pressed against it, suitable and similar pressures can be ensured for all points explored. A simple calibrating device is included. This consists of a small lever rocking on a jewel and engaging with the wooden indicators, to which it applies known pressures for calibration by means of a scale pan and weights. The weight of the wooden indicator and cover glass is of the order of 110 milligrams. The apparatus is illustrated in Fig. 19.

Results.—A number of observations have been made on various types of telephone receivers, and particulars of some of these will now be given :—

Tests have been made of the resonant frequency of the fundamental of a Bell receiver, by listening, by the cemented-on type of indicator, and by the bifilar indicator, and all agree to within about 50 cycles. The amplitudes of motion by the two methods of

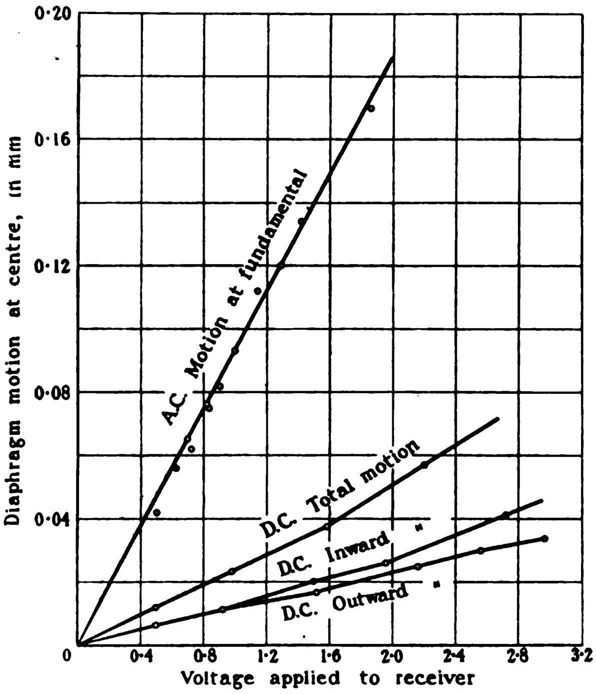


FIG. 20.—Amplitude of motion at centre of Bell receiver diaphragm for direct current and alternating current at fundamental.

diaphragm measurement are in approximate agreement.

Amplitudes of motion at centre of diaphragms for alternating currents at the fundamental frequency, and for direct currents.—The amplitude of motion of the centre point of the diaphragm of a 60-ohm Bell receiver

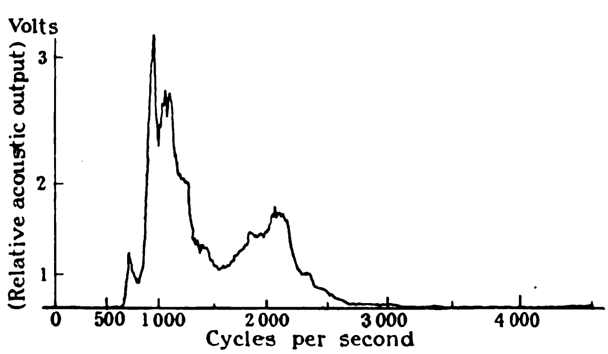


FIG. 21.—Characteristic of horn-type loud-speaker (type 1).

of the ordinary pattern was measured for various d.c. voltages across the receiver for both directions of application.

Fig. 20 gives curves for the motions towards and away from the poles, and it will be noted that for values above 1 volt the motions towards are greater than those away from the poles. In the same figure a curve is also given showing the sum of the inward and outward motions, and also a curve for the motion with alternating voltages at the fundamental diaphragm frequency. It will be noted that, for the limits investigated, this relationship follows a straight-line law and also that a steady voltage of 1 volt applied in both directions gives a diaphragm motion of 0·024 mm, whilst 1 volt (R.M.S.) at the fundamental frequency of the diaphragm gives a motion of 0·093 mm, or about four times as much.

Frequency Characteristics of Loud-Speakers.

By means of the eddy-current transmitter and the heterodyne oscillator, photographic records were obtained of different types of loud-speakers. Some typical examples of these are reproduced, brief details of which follow. The voltages shown on these curves bear no relationship to the eddy-current transmitter calibration which appears in Fig. 6.

Fig. 21 is the characteristic of a horn-type loud-

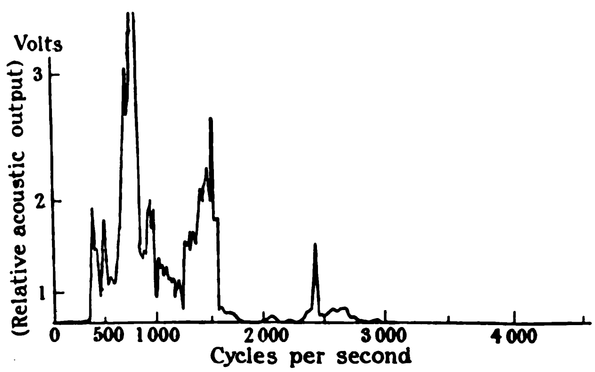


FIG. 22.—Characteristic of horn-type loud-speaker (type 2).

speaker having a circumferentially corrugated diaphragm the centre of which is connected to an armature. The horn expands from an internal cross-sectional area of

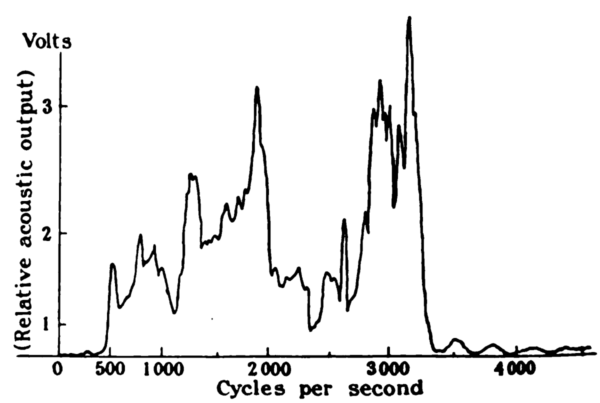


FIG. 23.—Characteristic of horn-type loud-speaker (type 3).

0·32 sq. in. to one of 0·5 sq. ft., the axial length being approximately 20 in. This record was taken with the loud-speaker and transmitter in the open air at some distance from buildings.

Fig. 22 was taken using another horn-type loud-speaker; in this case the diaphragm was a stalloy disc, $2\frac{3}{4}$ in. free diameter by 0·015 in. thick. The horn was

of metal, the extreme cross-sections being 0·25 sq. in. and 1 sq. ft., and the axial length about 28 in.

Fig. 23 shows the characteristic of a telephone head-gear watch-type receiver, used as a loud-speaker, with

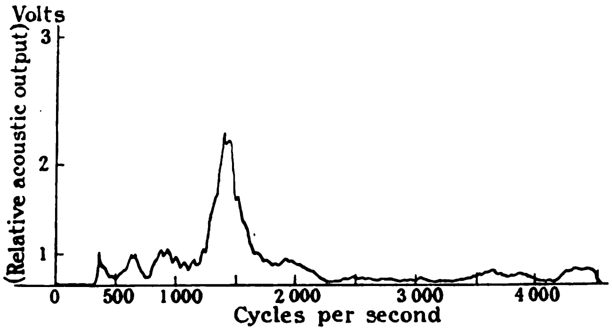


FIG. 24.—Characteristic of hornless loud-speaker (type A).

an exceptionally well-designed horn. This horn expands, according to an exponential law, from a cross-section of 0·2 sq. in. to one of 1 sq. ft.; the axis of the horn is straight and 3 ft. in length.

Figs. 24 and 25 show the performance of two types of hornless loud-speakers. That in Fig. 24 is of the pleated diaphragm type, the diaphragm having a diameter of about 1 ft.; whilst the diaphragm of the one shown in Fig. 25 is umbrella-shaped and very light. In both

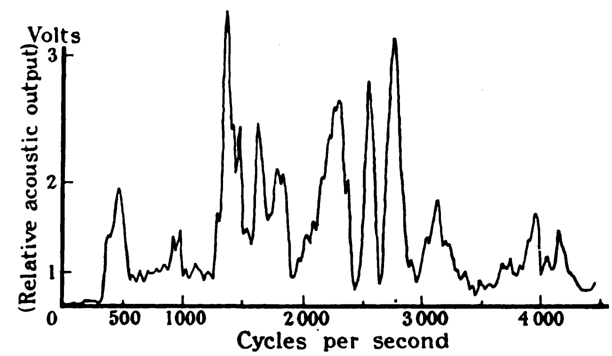


FIG. 25.—Characteristic of hornless loud-speaker (type B).

cases the centre of the diaphragm is connected by a pin to the armature of an electromagnetic system.

The curves of Figs. 22, 23 and 24 were taken in a cabinet which had been draped to minimize sound reflections, whilst that of Fig. 25 was taken in a large room without any special precautions to overcome reflections, which may have considerably modified the characteristic.

FREQUENCY CHARACTERISTICS OF LINES.

Uniform lines.—This covers all types of unloaded and unrepeatered lines, both underground and aerial. The well-known formula for the voltage or current attenuation along a uniform line is

$$a = \sqrt{\{\tfrac{1}{2}\sqrt{[(R^2 + L^2\omega^2)(G^2 + C^2\omega^2)]} + \tfrac{1}{2}(RG - LC\omega^2)\}}$$

where R = resistance per unit length of circuit,
L = inductance ,, ,,
C = capacity ,, ,,
and G = leakance.

Fig. 26 shows the value of a calculated for two typical lines: (1) a 20-lb. underground cable and (2) a 400-lb. aerial line. It will be seen that the attenuation of the unloaded cable increases with the frequency, being, in fact, proportional to $\sqrt{}$(frequency), whereas the attenuation of the heavy-gauge open wire is substantially constant.

These curves explain the well-known fact that unloaded cable circuits, when of any length, are always "drummy," due to the greater attenuation of the higher frequencies, whereas the open-wire line, when in good condition, is nearly perfect.

The line constants per mile of circuit are :—

20-lb. cable.—$R = 88$ ohms, $L = 0$, $C = 0{\cdot}06\mu$F, $G = 0$.

400-lb. open wire.—$R = 4{\cdot}5$ ohms, $C = 0{\cdot}0092\mu$F, $L = 3{\cdot}44 \times 10^{-3}$ H, $G = 10^{-6}$ mho.

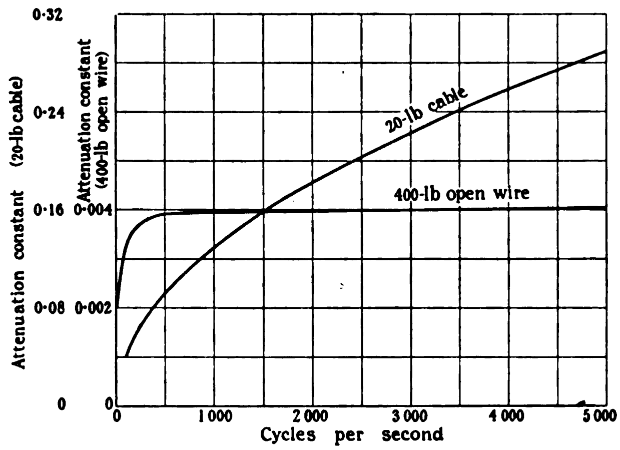


FIG. 26.—Characteristic of unloaded cable and open wire.

Loaded lines.—In spite of the electrical efficiency of open-wire circuits, the obvious maintenance difficulties and the physical impossibility of finding room for the large numbers of circuits necessary for modern requirements, even apart from the question of cost, have resulted in the development of loaded lines. Most modern long-distance lines in the British Isles consist of 20-lb. or 40-lb. conductors with different types of loading coils spaced at different intervals. The following are the standard loadings adopted :—

Extra light, heavy	0·044-henry coils spaced at	1·125 m
Light, light ..	0·136 ,, ,, ,, ,,	2·6 m
Half medium, heavy	0·089 ,, ,, ,, ,,	1·125 m
Medium, medium..	0·177 ,, ,, ,, ,,	1·6 m
Medium, heavy ..	0·177 ,, ,, ,, ,,	1·125 m
Heavy, heavy ..	0·250 ,, ,, ,, ,,	1·125 m

The theory of the action of inductive blocks in a telephone line was worked out by M. I. Pupin and G. A. Campbell.* The latter showed that when $\frac{1}{2}\omega d\sqrt{(LC)}$ (where $\omega = 2\pi \times$ frequency, L = coil inductance per unit length, C = capacity per unit length,

* *Philosophical Magazine*, 1903, vol. 5, p. 313.

and d = distance between coils), became equal to or greater than unity, the character of the transmission changed. The attenuation becomes largely independent of resistance, is caused by reflections between coils, and increases very rapidly with frequency, whereas below unity the attenuation is practically independent of frequency.

This curious change in transmission, which is the basis of all electrical filter circuits, obviously has a most important bearing upon the design of loaded lines. The greater the number of coils used in any line to give any specified inductance the higher will be the value of the frequency at which $\frac{1}{2}\omega d\sqrt{(LC)}$ becomes 1, and hence the higher will be the frequency at which the attenuation begins rapidly to increase, i.e. the "cut off" point. For economic reasons, however, as few coils as possible must be used, so that it is necessary to determine the maximum frequency which it is desired to transmit without serious attenuation. In the early days of loading it was found for the lengths of loaded

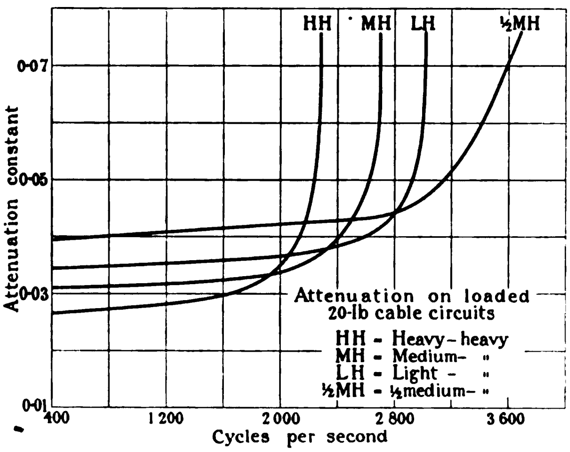


FIG. 27.—Characteristics of 20-lb. cable with various loadings.

circuit in use that a maximum frequency of about 1 800 cycles was sufficient for the transmission of commercial speech. With the introduction of thermionic repeaters, however, and consequent increase in length of loaded underground circuits, the effects, which are cumulative, of the somewhat greater attenuation of the higher frequencies in each repeater section, become important, and it has been found necessary to increase the cut-off point.

On existing loaded circuits the cut-off frequency varies between 2 000 cycles for the heavy-heavy loading to 5 600 for the extra light-heavy.

Fig. 27 shows the attenuation, calculated at different frequencies, of a number of 20-lb. circuits loaded with different coils at different spacings.

The constants taken for the cable were :—$R = 88$ ohms, $C = 0{\cdot}062\mu$F, $L = 1{\cdot}5 \times 10^{-3}$ H, $G = 10^{-6}$ mho.

Electrical transmission lines, when their constants are known, are simple structures which lend themselves readily to calculation. For this reason the curves shown in Figs. 26 and 27 have been calculated.

A direct measurement can, however, readily be made by means of the apparatus previously described. For this purpose the line under test must be terminated at the far end with an impedance equal to itself at all frequencies. This is most simply done, whenever possible, by using a line of sufficient length to prevent appreciable reflection from the far end reaching the measuring point. If E_s be the voltage input to the line at the sending end and E_l the voltage l miles down the line, then

$$\frac{E_l}{E_s} = e^{-\alpha l}$$

where α = attenuation constant per mile, and
e = base of Napierian logarithms.

TELEPHONE LINE REPEATERS.

Two systems of operating thermionic repeaters, known as the two-wire and four-wire, are in use. In the former, one pair of wires is used between stations and is used by each speaker, the repeater being duplex. In the four-wire system the subscriber receives incoming speech over one pair of wires and sends out his own speech over the other pair, and the repeaters in each pair are simplex, working in one direction only.

Fig. 28 shows the repeater connections in a two-wire circuit. As is well known, in a circuit of this type

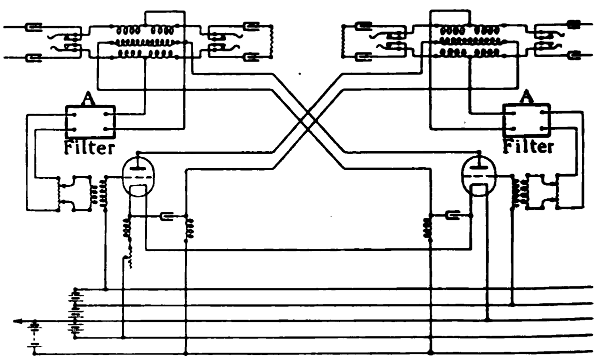


FIG. 28.—Two-wire repeater.

where a balanced transformer is used, unless the balance is kept within fairly close limits self-oscillation will occur, and this introduces a limiting frequency condition. The balances for any circuit are calculated from measurements made, over the frequency range, on the cable in which the repeater is to be used. Fig. 29 shows the measured values of resistance and reactance for an actual cable, together with those of the balancing circuit designed to be as nearly as possible equal to them.

The cable is 20-lb., with medium-heavy loading and the following constants :—$R = 88$ ohms, $C = 0{\cdot}065\mu$F, $L = 10^{-3}$ H, $G = 10^{-6}$ mho.

The small irregularities in the cable figures are due to irregularities in the constants of the cable or coils, or the spacing of the latter, and it will be seen that beyond about 1 900 cycles these irregularities become serious. In order to eliminate these effects the filter circuit shown at A in Fig. 28 is inserted. This filter is usually designed to cut off nominally at 2 200 cycles. Fig. 30 shows the amplification obtained with a commercial duplex repeater such as is shown in Fig. 28. For the test the repeater was inserted in the centre of 40 miles of non-reactive line of line impedance $1\,000\underline{/0}$ ohms, this being the line impedance for which the repeater

was designed. Each line, as is usually the case in practice, was terminated at the repeater with a balanced transformer. The voltage measurements were made at the two extreme ends of the 40 miles of line, the far end being terminated with the line impedance, viz. $1\,000\underline{/0}$ ohms. The curves shown give the amplification

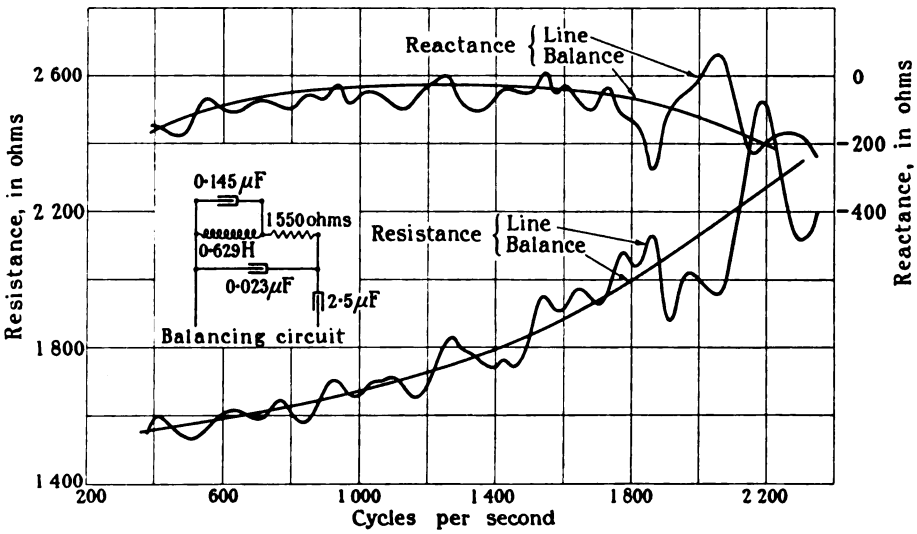


FIG. 29.—Impedance characteristics for loaded line and equivalent balancing circuit.

of the repeater alone, correction having been made for the voltage-drop in the two lines.

On these repeaters the degree of amplification can be adjusted by the potentiometer shown in Fig. 28, but the shapes of the two curves, with and without the filter, will not be sensibly changed.

It will be seen, therefore, that duplex repeaters impose an upper frequency limit of, at present, about 2 200 cycles, and also a lower limit of about 150 to 200 cycles.

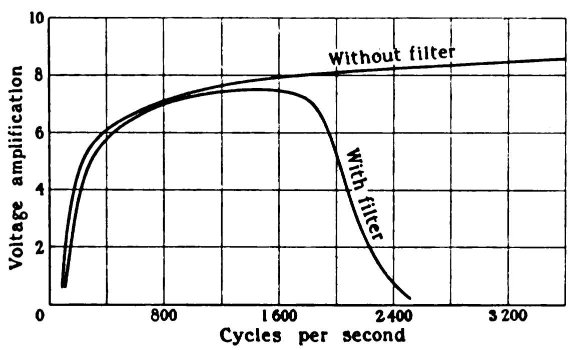


FIG. 30.—Characteristic of 2-wire repeater with and without filter.

Four-wire repeaters.—With four-wire repeater circuits no repeater balances are required and the frequency limitation is given by the loading of the line. As previously mentioned, there is an effect due to the cumulative slightly greater attenuation of the higher frequencies, which is only noticeable owing to the greater length of circuit permissible with repeaters.

IMPEDANCE AND POWER MEASUREMENTS BY MEANS OF HETERODYNE OSCILLATOR.

Another important use of the heterodyne oscillator and recording apparatus lies in the measurement of impedance and power. By adding a resistance in series with the apparatus under test and recording the oscillator P.D., the P.D. across the series resistance and the P.D. across the apparatus under test, a series of "three voltmeter" readings can be obtained at any desired frequency within the frequency range, and the power dissipated in the apparatus calculated from the well-known formula

$$\text{Watts} = \frac{1}{2R}(E_1^2 - E_2^2 - E_3^2)$$

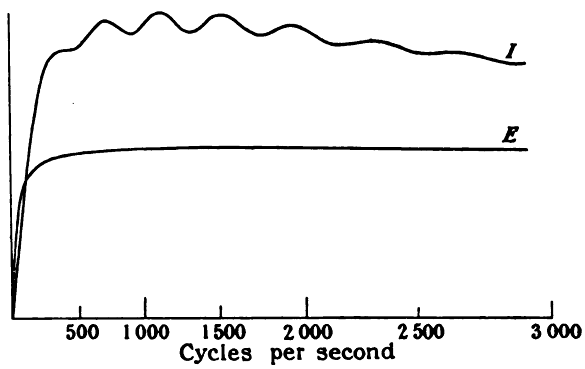


FIG. 31.—Input current on aerial line with fault.

A particularly valuable application to impedance measurements lies in the use of the heterodyne oscillator for the location of faults in telephone lines. Should there be any discontinuity in the uniformity of a telephone line carrying an alternating current, the irregularity, as is no doubt well known, will cause partial reflection of the current wave, with the result

that standing waves of current and voltage will be produced along the line. Advantage is taken of this to locate the position of the irregularity.

In the normal way impedance tests are made* at the sending end of the line over a considerable range of frequencies, and these are plotted against frequency. If there is a single irregularity the curve will be a wavy

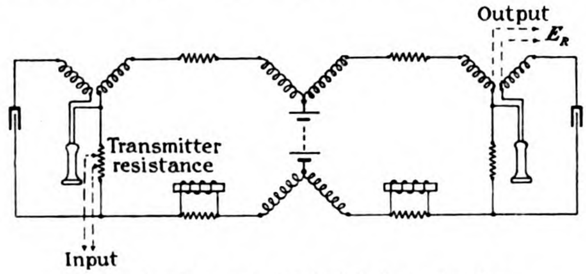


FIG. 32.—Repeating coil "A" connection.

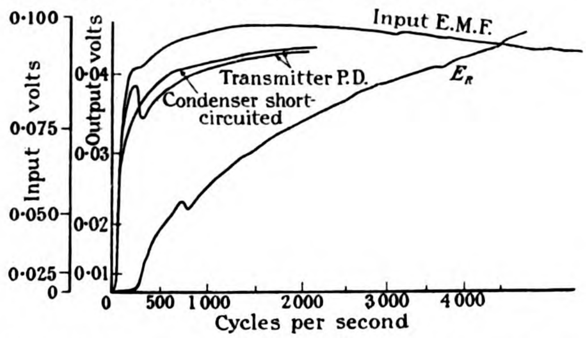


FIG. 32 (*a*).—Characteristics of repeating coil "A" connection.

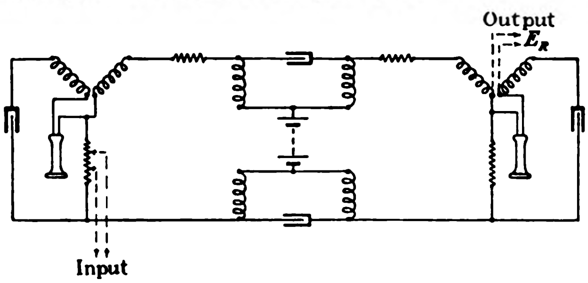


FIG. 33.—Stone "A" connection.

line, the distance between peaks depending upon the distance of the irregularity as follows :—

If d = distance of the irregularity,

f_1, f_2 = frequencies at two adjacent peaks,

λ_1, λ_2 = corresponding wave-lengths,

v_1, v_2 = corresponding velocities of propagation,

N = number of wave-lengths travelled by the reflected wave to and from the irregularity, i.e. in $2d$,

then $N = 2d/\lambda_1$ and $N + 1 = 2d/\lambda_2$.

Also, as $\lambda_1 = v_1/f_1$ and $\lambda_2 = v_2/f_2$,

$N = 2df_1/v_1$ and $N + 1 = 2df_2/v_2$;

from which, $$d = \frac{v_1 v_2}{2(f_2 v_1 - f_1 v_2)}$$

* See C. ROBINSON and R. M. CHAMNEY: Institution of Post Office Electrical Engineers, Paper No. 76.

Fig. 31 shows the input current for a constant applied voltage at the sending end of 500 miles of 200-lb. aerial line, terminated by its characteristic impedance, but with a shunt of 400 ohms across the line at 200 miles from the sending end. This is from a record taken by means of the heterodyne oscillator. Taking the three pairs of adjacent maximum impedance points (occurring

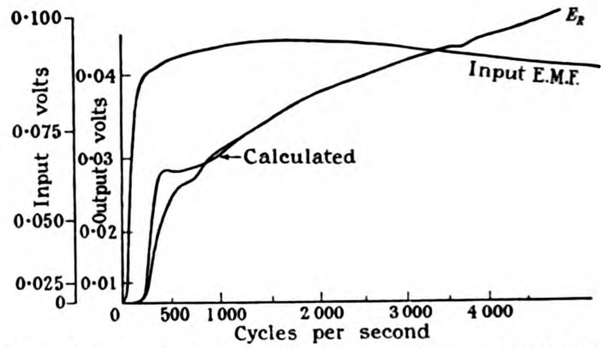


FIG. 33 (*a*).—Characteristics of "Stone" "A" connection.

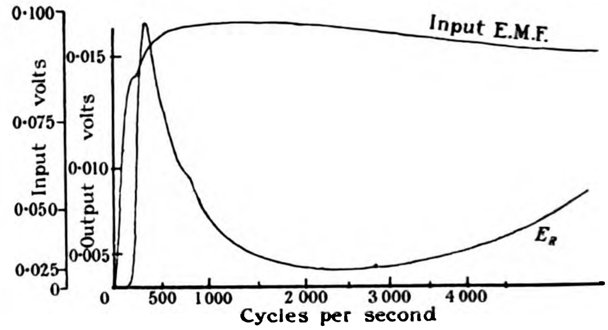


FIG. 33 (*b*).—Characteristic of Stone "A" connection; both induction coils reversed.

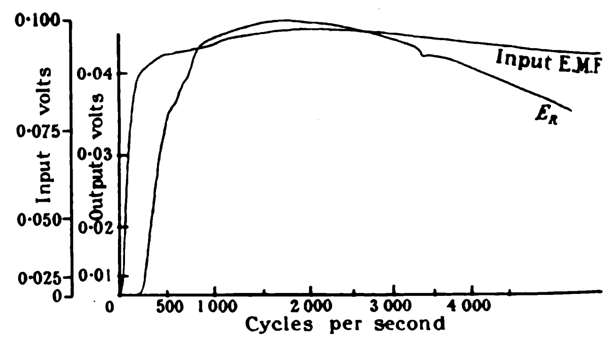


FIG. 33 (*c*).—Characteristic of Stone "A" connection; receiving-end induction coil reversed.

at 910 and 1 340 cycles, 1 340 and 1 760 cycles, 1 760 and 2 170 cycles) the values found for d are respectively 195, 196 and 200 miles.

It is obvious that the test made with the oscillator is very much quicker and less laborious than the corresponding tests of impedance made by means of a bridge.

TELEPHONE EXCHANGE CONNECTIONS.

Figs. 32, 33 and 34 show three typical exchange connections with their corresponding frequency charac-

teristics. The effects of exchange apparatus depend upon the lines on which it is used, and it was thought that the most satisfactory way of indicating results would be to make an overall voltage measurement of sent and received voltages over a complete telephone connection. It is known that a telephone transmitter in operation may be represented by a steady resistance in which an E.M.F. may be supposed to exist, and advantage was taken of this. The

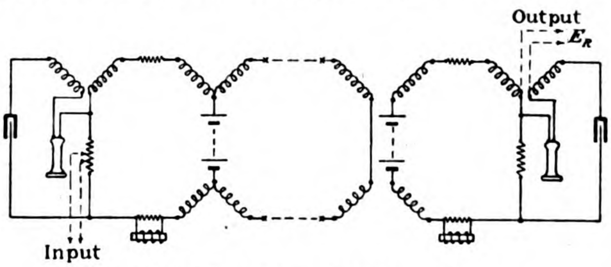


FIG. 34.—Local junction connection.

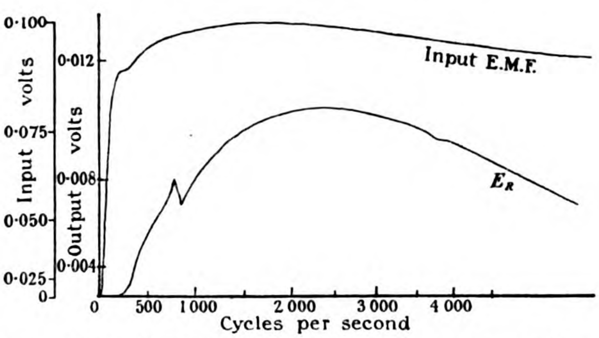


FIG. 34 (*a*).—Characteristics of local junction connection, with non-reactive cable.

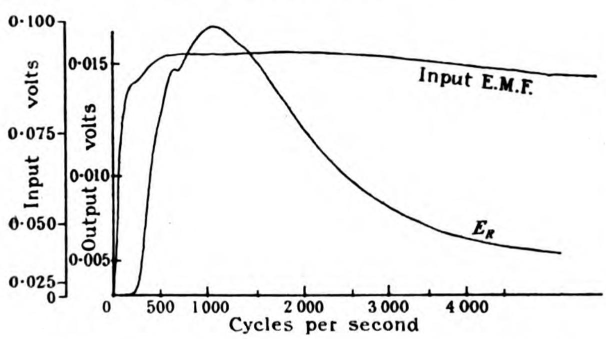


FIG. 34 (*b*).—Characteristics of local junction connection, with 20 lb. cable.

transmitter of the sending-end instrument is replaced by a resistance of 50 ohms. A fraction of this forms part of the non-inductive load of the heterodyne oscillator. The P.D.'s across this fraction and also across the receiver at the far end are recorded photographically.

Fig. 32 (*a*) shows the normal " A " repeater cord circuit, transmitter E.M.F., transmitter P.D., and transmitter P.D. with sending-end condenser short-circuited

Fig. 33 (*a*) shows the normal " A " cord circuit (Stone type); (*b*) is the " A " Stone circuit with one of the induction-coil windings at each end reversed; (*c*) shows one coil winding reversed at the receiving end.

Fig. 34 (*a*) shows the characteristic of a junction circuit with 8 miles of non-reactive cable, and (*b*) the same with 8 miles of 20-lb. cable.

The most noticeable feature of each characteristic is the fact that there is practically no voltage on the receiver terminals until a frequency of about 250 cycles is reached, at which point there is a very rapid rise of voltage, followed by a more or less uniform value. The explanation lies in the rather unusual connections of the standard-type common-battery instrument circuit. It can be shown that the circuit given in Fig. 33, for example, is equivalent to that shown in Fig. 35, the

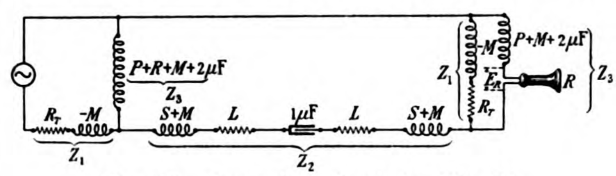


FIG. 35.—Equivalent circuit for Fig. 33.

relatively high-impedance current-feeding coils being neglected.

In Fig. 35:—

R_T = transmitter resistance,
M = mutual impedance of instrument induction coil,
S = impedance of secondary of coil,
P = impedance of primary of coil,
R = impedance of receiver,
L = local line resistance.

Inserting the values for the different quantities, Table 4 shows the value of Z_1, Z_2, Z_3, at different frequencies, together with the calculated voltage upon the far-end receiver for a constant input E.M.F.

TABLE 4.

Frequency	Z_1	Z_2	Z_3	E_R (Relative P.D. on receiver)
64	66/33	2 570/90	1 170/89	—
160	100/64	690/75	285/71	8
240	142/72	235/45	96/7	68
320	186/76	235/45	230/66	220
400	225/79	465/69	377/75	246
480	270/81	690/76	525/78	239
640	360/85	1 120/78	800/79	239
1 120	630/87	1 860/82	1 340/79	272

It will be seen that both Z_2 and Z_3 have a minimum impedance at about 250 cycles and that calculation

gives the same sharp rise of voltage at about this frequency, as shown by the experimental records. The effect is mainly caused by the effect of frequency upon Z_3. The calculated curve is plotted upon the photographic record in Fig. 33 (*a*). The same effect is obtained if the retard coil feed is replaced by a repeater coil feed. The general shape is the same in the calculated and experimental cases, the differences being no doubt due to the fact that the exact values of the various constants have not been taken. At the low frequencies the receiving end portion of the circuit containing the receiver is of high impedance and is shunted by the low impedance Z_1 until resonance is reached.

The small dip in voltage noticeable in each curve at about 800 cycles is due to the drop in receiver impedance at the fundamental resonant frequency, and that noticeable at about 3 600 cycles is due to the nodal circle resonance. The exact shape and position of the dip at the fundamental frequency depends upon the amount of air damping on the diaphragm.

With no cable in circuit, the instrument and cord circuit characteristics, after the first sharp rise, are steady or rising. The effect of cable in attenuating the higher frequencies is well shown in Fig. 34 (*b*).

Referring to Fig. 33 (*a*), (*b*), (*c*), it will be seen that the effect of reversing the induction-coil windings is very pronounced and is due almost entirely to reversal at the sending end. As a matter of fact, reversal at this end causes a loss of about 8 miles of standard cable, and at the receiving end a gain of about 0·5 miles. The reversal changes + M to − M, and this practically reduces Z_3 to $R + 2\ \mu F$, thus producing a heavy shunt at the sending end.

In Fig. 32 (*a*) are shown the transmitter P.D., both with and without the condenser in circuit. At the commencement, owing to the high impedance of the circuits, the P.D. and E.M.F. are nearly the same. As Z_3 approaches resonance the increased current causes an increased voltage-drop in the transmitter, and hence a reduced P.D., which is shown on the transmitter P.D. curve. After passing resonance, the impedance of Z_3 rises continuously with frequency, and the voltage-drop in the transmitter falls. It will be seen, therefore, that the standard type of telephone instrument imposes a definite lower limit of about 250 cycles, just as the loaded line imposes a higher limit.

Frequency Characteristics of Audio-Frequency Amplifiers.

The heterodyne oscillator has proved a convenient means for the rapid determination of the frequency characteristics of telephone-frequency amplifiers. The word "amplifier" here is intended only to cover the use of valves for increasing an applied alternating voltage, and "the amplification of one stage" to refer to the ratio of the voltage on the grid of one valve of an amplifier to that on the grid of the preceding valve.

The majority of tests have been made on individual stages of amplification, mostly of the transformer-coupled type. The tests made on resistance-capacity couplings confirm the estimated performances of such circuits, but the tests on intervalve transformer circuits show such a variety of results—even with the same transformer, used in conjunction with different valves—that further remarks on this method of coupling seem to be justified.

The performance of the transformer depends largely on the constants of the circuit with which it is used, and especially on (*a*) the impedance of the valve used in the primary circuit, (*b*) the capacity load on the transformer secondary, and (*c*) the presence of grid current in the secondary winding. It is probable that the value of the impedance in the plate circuit of the second valve will, under some conditions, also exert an influence on the frequency characteristics of the transformer, but this point has not been investigated.

Methods of test.—An intervalve transformer was tested by inserting it, in the normal manner, between two valves of known constants, by recording the input to the grid of the first valve (this input is a fraction of the substantially constant output from the heterodyne oscillator), by taking a photographic record of the output, through a resistance-capacity coupling, from the second valve, and by ensuring that both valves were operating under normal conditions for amplification and that no grid currents were allowed to flow.

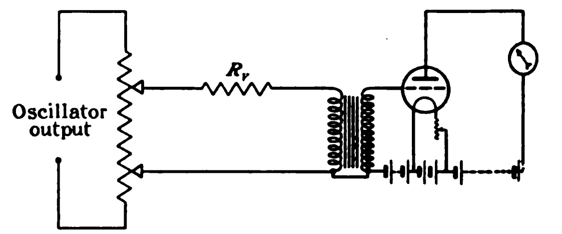


FIG. 36.—Intervalve transformer testing-circuit.

For an alternative method of test, the first valve was replaced by a non-inductive resistance R_1, and the second valve was operated as a rectifier on the anode rectification principle, the reflecting galvanometer being inserted in the plate circuit. (In this circuit—shown in Fig. 36—the direct current normally present in the primary winding of the transformer has been omitted, though current can be made to flow, if required, by the insertion of a high-tension battery. The effect of this current in magnetizing the transformer is usually negligible.) It is considered that this circuit represents, to a very close approximation, the normal working condition of an intervalve transformer so far as the frequency characteristic is concerned.

The amplification to be expected at a given frequency when a valve of amplification factor μ replaces the resistance R_1 will be the product of μ and the ratio of output to input voltages at that frequency. An advantage of this simplified circuit is the ease with which the characteristics are obtained for the equivalent of valves of different and known impedances in the primary circuit.

Intervalve Transformer Curves.

Some typical curves have been selected for reproduction in Figs. 37, 38, 39 and 40, of which those in Figs. 37, 38 and 39 were obtained from a transformer in circuit

between two valves, whilst for those in Fig. 40 the first valve was replaced by a non-inductive resistance, the circuit of Fig. 36 being used.

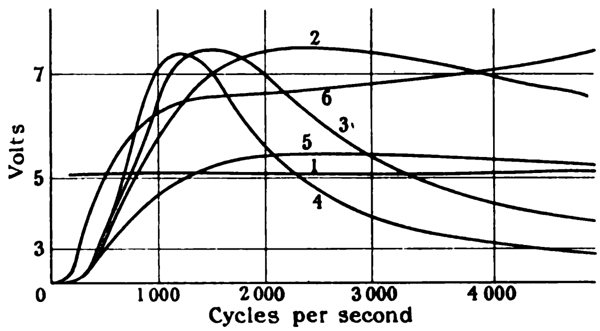


FIG. 37.—Characteristics of intervalve transformer " A."

Fig. 37 shows the performance, under different conditions, of transformer A, which is of ordinary type and commercial manufacture and has a 4 : 1 ratio of turns. In this figure, curve 1 is the oscillator output characteristic; curve 2 shows the performance of the transformer as normally connected (I.P. to plate, O.S. to grid); curves 3 and 4 were taken with loads of 100 and 200 $\mu\mu$F respectively on the secondary, and curve 5 with a load of 50 000 ohms on the primary; for all these curves a valve of about 20 000 ohms impedance was used in the primary circuit. Curve 6 was taken with the transformer normally connected but with this valve replaced by one of about 6 000 ohms impedance.

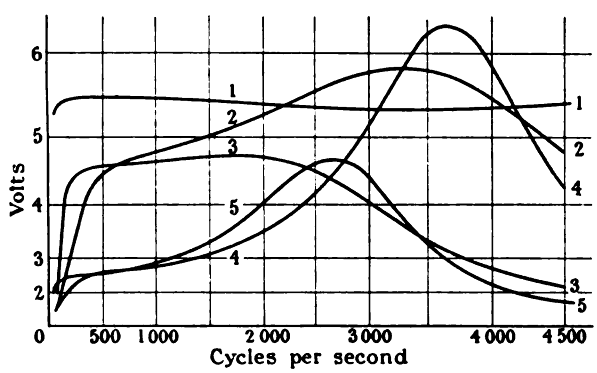


FIG. 38.—Characteristics of intervalve transformer " B."

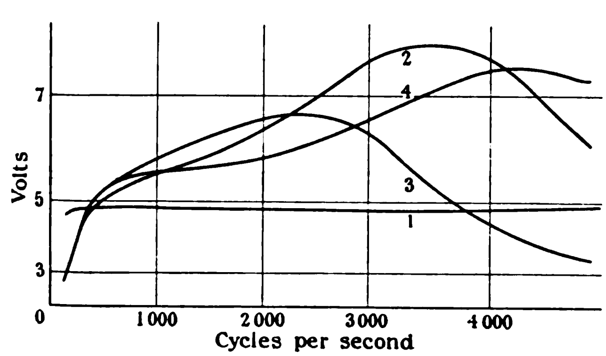


FIG. 39.—Characteristics of intervalve transformer " B."

Fig. 38 shows the performance of transformer B, also of commercial manufacture and having a 4 : 1 ratio of turns. This transformer was constructed in the form of slab coils round a heavy closed iron core, and from this construction an exceptionally high value of magnetic leakage is to be expected. Curve 1 shows the oscillator characteristic; curves 2 and 3 the performance of the transformer with the connections normal and with the secondary reversed, respectively, using a valve of 20 000 ohms in the primary circuit; and for curves 4 and 5 a 6 000-ohm valve was used, curve 4 representing normal connections and curve 5 a reversed secondary.

Transformer B was used for the curves of Fig. 39, in which curves 1 and 2 are for the same conditions as curves 1 and 2 of Fig. 38; curve 3 was taken with a capacity load of 50 $\mu\mu$F on the secondary, and curve 4 with a load of 1 000 $\mu\mu$F on the primary.

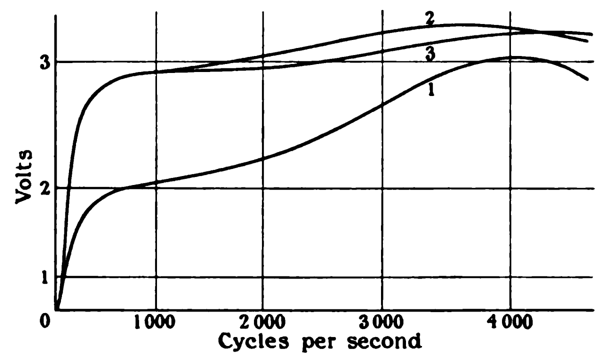


FIG. 40.—Characteristics of intervalve transformer " B."

The curves of Fig. 40 were obtained using a transformer of the same make as B on the circuit of Fig. 36, the resistance R_1 being 20 000 ohms. Curve 1 represents normal connections; curve 2 a load of 1 megohm on the secondary, and curve 3 loads of 1 megohm on the secondary and 750 $\mu\mu$F on the primary. The input voltage in the case of curves 2 and 3 was twice that of curve 1.

The appended analysis, using the equivalent T circuit of the transformer, is submitted in explanation of the results obtained from these tests.

CONCLUSION.

It will be observed that the greater part of this paper deals with the apparatus and methods required to measure and record directly the frequency/amplitude characteristics of lines, circuits, transformers, repeaters, transmitters, and receivers of ordinary and loud-speaker types.

It is obvious that in one paper it is impossible to deal adequately with the frequency characteristics of all apparatus used for the transmission of speech and music, and little attempt has been made to do more than indicate the results obtained with typical apparatus of each of the various classes. The few characteristics given indicate the highly resonant output of commercial telephone receivers and transmitters and the

extent to which the volume efficiency must depend upon resonance. These characteristics show that there is considerable room for improvement in the case of receivers and transmitters, and it is claimed that the apparatus described forms a ready means of enabling the effects of change in construction and design to be conveniently observed, measured and recorded.

The authors' acknowledgments are due to Colonel Purves, Engineer-in-Chief of the Post Office, for permission to present this paper, and to the staff of the Post Office Engineering Research Station for valuable assistance and co-operation.

APPENDIX.

Equivalent Circuits of Intervalve Transformers.

Fig. 41 shows the equivalent T circuit of an intervalve transformer referred to the primary circuit.* R_V represents the internal resistance of the first valve; L_1, R_1, and L_2, R_2, the primary and secondary (referred to the primary) leakage impedances respectively; L, R, the mutual impedance, and C_2 the combined secondary capacities, internal, mutual † and external, all referred to the primary circuit. The capacities of the primary winding have been omitted, since their effect is in

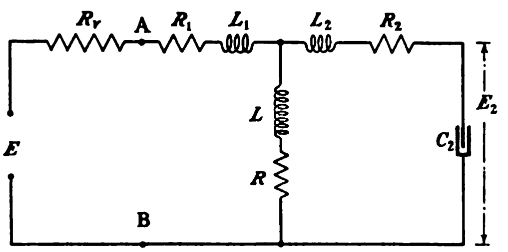


Fig. 41.—Equivalent intervalve transformer circuit.

general negligibly small; the effect, under special circumstances, of adding capacity across the primary will be mentioned later.

Since the impedance to the right of the points A, B, will vary with the frequency of the impressed voltage E (which is $\mu \times$ voltage on the grid of the first valve), the proportion which is applied to the transformer terminals will depend upon the primary impedance of the transformer. This impedance increases with the frequency from a low to a high value as compared with R_V, up to a critical frequency determined by the resonance of L with C_2, after which it will decrease continuously (or at least as far as a frequency determined by the resonance of L_1 and L_2 with C_2). This explains the more or less gradual rise of the frequency/amplitude curves at low frequencies, and the greater rapidity of the rise obtained when a valve of lower impedance R_V is used. As the frequency is increased beyond this critical value the amplitude is liable to be affected by two opposing influences; one of these, due to the decreasing primary impedance, tends to decrease the voltage across A B and therefore across C_2; the other is the tendency of the voltage across C_2 to increase in proportion to that across A B as the frequency approaches a second critical value determined by the resonance of L_1 and L_2 with C_2. Beyond this point the amplitude may be expected to fall off continuously with an increase in the frequency.

An expression can be obtained for the ratio $E_2 : E$ from the circuit of Fig. 41, but it has little value since the quantities of the circuit are all more or less variable with the frequency. It is of interest, however, to investigate the performances of intervalve transformers from theoretical considerations by means of approximate equivalent circuits, which are generally applicable over a limited range of frequency.

Case 1. The Resonance of L with C_2.

It has been demonstrated * that for a wide range of frequencies in the neighbourhood of this resonance, which range extends down to very low frequencies, the performance of an intervalve transformer can be represented to a close approximation by that of the circuit shown in Fig. 42, in which the resistances R_3 and R_4 are considered to be invariable with the frequency. For this circuit

$$\left[\frac{E}{E_2}\right]^2 = \left[\frac{R_V R_4}{R_4^2 + \omega^2 L^2} + \frac{R_V}{R_3} + 1\right]^2 + \omega^2 R_V^2 \left[C_2 - \frac{L^2}{R_4^2 + \omega^2 L^2}\right]^2 . \quad (1)$$

The critical frequency giving a minimum value of E/E_2 is given by

$$\omega_1^2 = \frac{1}{C_2 L}\left\{-\frac{R_4^2 C_2}{L_2} + \sqrt{\left[\frac{2R_4^2 C_2}{L} + \frac{2R_4}{R_V}\left(\frac{R_V}{R_3}+1\right)+1\right]}\right\}$$

In general it will be found that the quantity $R_4^2 C_2/L$ is negligibly small, so that the equation becomes

$$\omega_1^2 = \frac{1}{C_2 L}\sqrt{\left[1 + \frac{2R_4}{R_V}\left(\frac{R_V}{R_3} + 1\right)\right]} \quad . \quad . \quad (2)$$

at which value

$$\left[\frac{E}{E_2}\right]^2 = \left\{1 + \frac{R_V}{R_3} + \frac{R_V R_4 C_2}{L\sqrt{\left[1+\frac{2R_4}{R_V}\left(\frac{R_V}{R_3}+1\right)\right]}}\right\}^2 + \frac{C_2 R_V}{L}\sqrt{\left[1+\frac{2R_4}{R_V}\left(\frac{R_V}{R_3}+1\right)\right]} \left\{1 - \frac{1}{\sqrt{\left[1+\frac{2R_4}{R_V}\left(\frac{R_V}{R_3}+1\right)\right]}}\right\}^2 \quad . \quad . \quad . \quad . \quad (3)$$

This quantity can never be less than unity, though, in general, it is nearly equal to unity. It should be remarked that if R_V be replaced by a valve of the same internal resistance and of amplification factor μ, then the amplification of the stage will be $\mu n E_2/E$, where n is the ratio of the secondary to the primary turns, and E_2/E is the value found from the equivalent circuit.

It is seen from equation (1) that the effect of using a lower resistance R_V will be to reduce the value of

* C. P. Steinmetz: "Alternating Current Phenomena."
† D. W. Dye: "The Performance and Properties of Telephone Frequency Intervalve Transformers," *Experimental Wireless*, 1924, vol. 1, p. 691, and vol. 2, pp. 12 and 74.

* D. W. Dye, loc. cit.

E/E_2, i.e. to raise the amplification, and that this effect is more marked as the frequency is made more remote from that given by ω_1, where the value of E/E_2 is normally nearly equal to unity. This effect is demonstrated in the cases of all the transformers that have been tested. It can also be shown that, for a given value of C_2L, i.e. approximately of ω_1, the frequency characteristic is improved by increasing the ratio $L : C_2$, a feature which is recognized in the design of some tranformers.

The effect of an external non-inductive load.—The effect, at the frequencies under consideration, of an external non-inductive load on either winding of the transformer may be investigated by means of the above equations. The presence of the external shunt will reduce the value of R_3.

At frequencies near the critical frequency the second term on the right of equation (1) is small as compared with the first, hence approximately

$$\frac{E}{E_2} = \left[\frac{R_V R_4}{R_4^2 + \omega^2 L^2} + \frac{R_V}{R_3} + 1\right]$$

Now, since a change in the value of E/E_2 for a given (small) change in ω is the same for any value of R_3, it

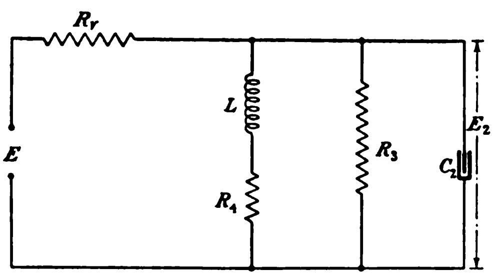


FIG. 42.—Equivalent transformer circuit; approximation for lower frequencies.

follows that the proportional change in E/E_2 will be less as the value of R_3 is reduced. Therefore the characteristic will, in the neighbourhood of the critical frequency, become more flattened out and reduced as to the value of its ordinates due to the presence of an external non-inductive shunt. Moreover, since the second term on the right of equation (1) is independent of R_3, it is clear that as this term becomes larger as compared with the first term (i.e. as the frequency is further removed from the critical value ω_1), so the effect of the shunt on the amplification becomes proportionately less.

CASE 2. THE RESONANCE OF L_1 AND L_2 WITH C_2.

Where this resonance occurs at a frequency considerably higher than that under Case 1, for the consideration of the performance of a transformer over a limited frequency range enclosing the resonance, the approximate equivalent circuit of Fig. 43 may be used. This circuit involves the assumption that the impedance L, R, is so large that its effect is negligible, and that, over the range of frequencies considered, variations in the values of $R_0(= R_1 + R_2)$ and $L_0(= L_1 + L_2)$ and C_2 with frequency may be neglected. In this case, therefore,

$$[E/E_2]^2 = (R_V + R_0)^2 C_2^2 \omega^2 + (L_0 C_2 \omega^2 - 1)^2 \quad . \quad (4)$$

This quantity is a minimum for a value ω_2 of ω given by

$$\omega_2^2 = \frac{1}{L_0 C_2}\left[1 - \frac{(R_V + R_0)^2 C_2}{2L_0}\right] \quad . \quad . \quad (5)$$

at which value

$$\left[\frac{E}{E_2}\right]^2 = \frac{(R_V + R_0)^2 C_2}{L_0}\left[1 - \frac{(R_V + R_0)^2 C_2}{4L_0}\right] \quad . \quad (6)$$

When ω_2 has a high value as compared with ω_1, in accordance with the above assumptions, it follows that $(R_V + R_0)^2 C_2/(2L_0)$ is less than unity, and for such values E/E_2 is less than unity, i.e. the amplification of the stage at the frequency given by ω_2 is greater than μn.

The effect of decreasing the value of $(R_V + R_0)^2 C_2/L_0$ by using a lower impedance R_V will be to raise the values of both ω_2 and the amplification at ω_2. Also, if C_2 be increased by means of an external capacity load on the secondary, the converse will apply.

The above equation for ω_2 may also be used to draw some general conclusions as to the influence on the characteristic of an intervalve transformer of the resonance of L_1 and L_2 with C_2. In the first place, it is

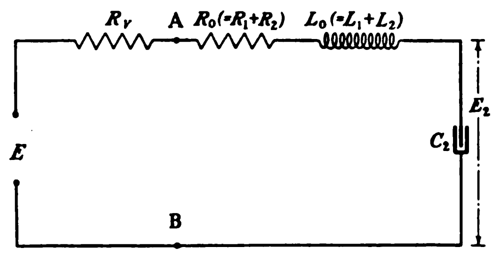


FIG. 43.—Equivalent transformer circuit; approximation for higher frequencies.

seen that there will be no real value for ω_2 unless $\frac{(R_V + R_0)^2 C_2}{2L_0} < 1$, and that as the value of this quantity is increased, the effect of this resonance on the characteristic will be reduced. Also for frequencies higher than ω_2 (or than ω_1 if $\omega_1 > \omega_2$) the amplification may be expected to fall off continuously as the frequency is raised.

Since the performance of the majority of intervalve transformers is chiefly open to criticism on account of their low amplification at frequencies below 1 000 cycles per sec. (especially when used with fairly high impedance valves, as is commonly the case), and since improvement in this direction can mainly be expected by lowering the value of ω_1 [see equation (2) above], it appears that this resonance of the leakage impedance is desirable at a frequency higher than that given by ω_1—at any rate when a high impedance R_V is used—in order to raise the point beyond which the amplification falls off continuously with increasing frequency, i.e. to increase the range of frequencies over which a large amplification is obtained. To effect this, since $(R_V + R_0)^2 C_2/(2L_0)$ must be < 1, and limits are set to

the values of R_V and C_2 by the external circuit conditions, it follows that L_0 should not be made too small, i.e. the coefficient of coupling between the windings should not be too high.

The effect of a capacity load on the primary.—It has been observed that the presence of a condenser across the primary winding of an intervalve transformer may have the effect of raising the value of the critical frequency given by ω_2 as well as of lowering the value of ω_1. (Similar effects have been observed with radio-frequency intervalve transformers.) This results in some cases in an improved characteristic, since the range of high amplification is extended; if, however, too large a capacity is used the characteristic will fall off before it rises to the final critical frequency.

An approximate analysis, using the equivalent circuit of Fig. 43 with an additional capacity included across the points A, B, shows that the above effects are to be expected, and that in the particular case where the added capacity is equal to C_2 (i.e. to the sum of the secondary capacities multiplied by the square of the ratio of secondary to primary turns) the decrease will occur if the value of $L_0/(R_V^2 C_2)$ is less than about 2.

The effect of a non-inductive load on the secondary winding.—Where resonance of the leakage inductance occurs, the effect of a non-inductive load on the secondary winding may be studied by considering a resistance S, representing this load, to be inserted across the condenser C_2 in Fig. 43.

For this circuit

$$\left[\frac{E}{E_2}\right]^2 = \left[\frac{R_V + R_0}{S} - (C_2 L_0 \omega^2 - 1)\right]^2 + \left[(R_V + R_0)C_2\omega + \frac{L_0\omega}{S}\right]^2 . \quad (7)$$

The critical value (the maximum value of E_2/E) is found at

$$\omega_2^2 = \frac{1}{C_2 L_0}\left[1 - \frac{(R_V + R_0)^2 C_2}{2L_0} - \frac{L_0}{2C_2 S^2}\right] \quad (8)$$

to be

$$\left[\frac{E}{E_2}\right]^2 = \left[(R_V+R_0)C_2+\frac{L_0}{S}\right]^2 \times \left[\frac{1}{C_2 L_0} - \frac{(R_V+R_0)^2}{4L_0^2} + \frac{1}{2SC_2}\left(\frac{R_V+R_0}{L_0} - \frac{1}{2SC_2}\right)\right] . \quad (9)$$

It is seen that the presence of S thus lowers the value of ω_2, and that unless $\frac{1}{S^2} < \frac{2C_2}{L_0} - (R_V + R_0)^2$ there can be no real value for ω_2. An examination of equation (9) shows that, as $1/S$ is increased from zero, the amplification at ω_2 is decreased continuously for all values of $1/S$ consistent with a real value of ω_2.

The use of a non-inductive shunt therefore tends to smooth out the frequency characteristic in both the cases considered above—at the expense of some sacrifice in amplification. It helps, moreover, to stabilize an amplifier which has any tendency to self-oscillation. It therefore provides a sometimes convenient alternative to replacing an intervalve transformer by one of a lower ratio, in cases where it is desired to replace the valve in the primary circuit by one of a higher impedance and higher amplification factor.

The foregoing analysis is applied only to individual stages of amplification. In general, the amplification of a multi-stage set will be the product of those of the individual stages at any given frequency. Exceptions occur, of course, when reaction is permitted and when the influence of the impedance in any plate circuit on a previous grid circuit is apparent.

A useful method of improving the performance of an intervalve transformer at the low frequencies is described in a paper by R. W. King in the *Bell System Technical Journal* for October 1923. The primary impedance of the transformer is tuned by an added series capacity, and the battery voltage is applied to the plate of the valve through a choke (or resistance) of suitable impedance.

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DISCUSSION BEFORE THE INSTITUTION, 29 APRIL, 1926.

Mr. H. H. Harrison: The paper shows the steady growth of the interlinking of the technique of various branches of the weak-current art, also that we shall have presently to include in that statement the mechanical reproduction of speech by electro-mechanical means, such as the modern gramophone. The paper introduces us to the conception of the cut-off frequency as applied to transmission lines. The paper also lays stress on the importance of investigating the proportionality of response over a wide frequency range for all elements in the chain of whatever transmission means are under consideration. It is interesting to note that the idea of the band frequency has extended even to long-distance telegraphy. We find, for instance, that the best signal shape, in the case of long-distance telegraph cables or lines, is not necessarily attained by allowing all the frequencies which form the rectangular pulses to pass; it is much better to introduce band filters and cut off many of the components. This also helps to clear the line. The bibliography shows the vast amount of work which has been done in recent years, and the large number of workers. It is very gratifying to find that the Research Section of the British Post Office is not only cognizant of this work, but is itself making such weighty and original contributions. I am somewhat disappointed that the authors have made no reference to the transmission unit. I am myself a believer in the transmission unit, but we want to know, amongst other things, whether one or more lines having entirely dissimilar characteristics but the same value in transmission units can be considered as identical when receiving and sending conditions are the same. I should like to suggest two additions to the authors' bibliography. I believe I am correct in saying that Mr. Shepherd (of, I think, the Research Department of the Post Office) was the first to point out, in a short note in the *Electrician* a good many years ago, that an ordinary telephone line behaved as an electric filter and cut off at a definite frequency which could be calculated from the constants of the line. I would further suggest that the paper by Dr. Kennelly entitled "A Contribution to the Theory of Telephony," which also appeared in the *Electrician* and which dealt with the behaviour of a transmitter induction-coil line combination over a band of frequencies, be also included. The present paper is further evidence, if evidence be needed, of the fact that telephony—or perhaps it would be better to say "communication engineering"—is just as important as any other branch of electrical engineering The powers employed are insignificant—in many cases only of the order of milliwatts—and in the event of a short-circuit the results are not so spectacular as when dealing with 20 000, 30 000 or 40 000 kW, but the engineering considerations underlying the design of a telephone network are just as important as the design of a three-phase high-tension power transmission line.

Professor E. Mallett: The authors have collected together valuable information on work done by various investigators in various countries, and they have given us an exceedingly useful piece of apparatus of their own in the heterodyne oscillator. About two years ago Mr. Cohen exhibited this oscillator (or its predecessor) in this room, and showed how one could get a wide range of frequencies from it by simply turning one knob. That, of course, is extremely useful. The paper gives some details of how to set up the apparatus and make it work. The output is given in Fig. 8, but it should not be imagined that directly the apparatus is set up as shown in Fig. 7 the output shown in Fig. 8 will be obtained. At the City and Guilds College we have been trying for some considerable time to get the output as shown in Fig. 8 from an arrangement very similar to that shown in Fig. 7, and we have not quite succeeded. Although the paper deals with frequency characteristics it does not mention how the frequency is to be measured. We have had difficulties in that connection. It is not sufficient for accurate work to take the note frequency as the difference of the calculated frequencies of the two oscillators, because these frequencies (especially of high-frequency oscillators) do not remain constant. As another addition to the bibliography I should like to suggest Miller's book on "The Science of Musical Sounds." Miller shows that vowel sounds all consist of either one

frequency or two frequencies. It does not matter in what pitch one says the word "māā"; what really constitutes the "āā" sound is a frequency of 1 000 cycles. Other vowels are characterized by having two frequencies. For instance, the sound in "mat" has two frequencies, 800 and 1 840. For "met" the two are 691 and 1 593; for "mate," 488 and 1 427, and for "meat" 308 and 3 100. There are certain other sounds which have only one frequency: "mōō," for example, where the "ōō" sound has one frequency only—326. The result is that if one says "meat," the two frequencies for which are 308 and 3 100, and the telephone apparatus cuts off everything above 2 000 cycles, one is left with "moot," and if one says "tea" it sounds like "too." Judging from the diagrams of the output of the transmitters, one would certainly gather that with the ordinary local battery transmitter and the common-battery transmitter nothing above 2 000 cycles could ever get on to the line. So far as the receiver in Fig. 15 is concerned it receives well from 2 000 to 2 400 cycles, but there is nothing whatever between 1 000 and 2 000 cycles, so that these scientifically accurate pictures must be very carefully interpreted acoustically. As a matter of fact, one knows that the transmitter sends out some energy above 2 000 cycles, and the receiver is not wholly inert between 1 000 and 2 000 cycles. What happens apparently is that the ear does not appreciate differences of intensity of sound to the extent that one would expect. A sound with a particle velocity of, say, 2 cm per sec. would perhaps be judged only half as strong again as one with a velocity of 0·2 cm per sec. The ear very quickly gets saturated. Good music of the broadcast order seems to be in quite a different category from telephony; there we have to have everything transmitted. Broadcast can, in fact, be compared with the finished picture. As far as ordinary telephony is concerned, we are content with a rough sketch; so long as the main features are there, our intelligence enables us to fill in the rest and we get a proper idea of what is intended.

Mr. E. K. Sandeman: I am very interested in the heterodyne oscillator as a possible solution to the problem of producing a light-weight oscillator. A good oscillator of the Hartley type with all accessories, covering a range of 100–50 000 cycles, may weigh as much as 200 lb. Is there any chance of a heterodyne oscillator being made which would be appreciably lighter than this? The chief difficulty arises from the fact that large coils are necessary in order to filter at low frequencies. In the case of the heterodyne oscillator, filtering may be done at high frequencies, which is much simpler, and further, a fixed frequency filter can be used. In a good many cases it is not necessary to know the frequencies extremely accurately for the purpose of response-frequency measurement. In the present state of things, in interpreting response-frequency characteristics, it is not possible to discriminate seriously between, say, 3 000 cycles or 3 200, so that a slight error in frequency is not very serious. The accuracy of the heterodyne oscillator is capable of being maintained within much greater limits of accuracy than that. The accuracy of an ordinary valve oscillator operating with mica condensers and air-choke inductances is, I understand, of the order of 3 parts in 100 000 for a change in temperature of 1 deg. C. For a change in temperature of 20 deg. this means that in the case of a heterodyne oscillator employing beat frequencies of the order of 20 000 cycles there would be a maximum change at 100 cycles of 12 cycles in each oscillator, which seems quite a tolerable change for a great many purposes, even if both beat oscillators vary in different directions. Further, for very many purposes it would be possible to sacrifice constancy of output. It is stated on page 1033 that no account is taken of local irregularities in the sound wave due to the presence of the transmitter. This refers to the fact that when the transmitter is placed in the testing chamber it distorts the sound field, which, in the absence of the transmitter, is presumably of an intensity uniform throughout the chamber, and constant with frequency. It seems to me that the distortion in the sound field occasioned by the presence of the transmitter is part of the distortion caused by the transmitter, and should be reckoned as such, and therefore this particular point is perfectly justified, but it also seems that the attendant circumstances require clear definition. There is another point which should not be lost sight of, viz. that when a man is put in a sound field he also distorts it, and it is a nice question as to whether a microphone could not be said to be truly distortionless if it distorted the sound field in the same way as the human head, for some chosen position. It seems to me that the experiments described in the paper indicate that the time is coming when these points must be taken up seriously. Very similar experiments have been made in the research department of the Western Electric Co. at New York, where they have also been taking characteristics of acoustic apparatus and have obtained results similar to those of the authors. I do not quite understand why a great many of the characteristics were taken with the telephone transmitter placed opposite the sound-measuring device in free air, and it is difficult for me to see what meaning a response characteristic could have under these conditions. The only criterion of performance seems to me to be a response characteristic under actual operating conditions, and the performance of a telephone receiver operating into free air is a very different thing from that of a telephone receiver pressed against the ear. An approximate solution would appear to be given by the use of some form of artificial ear.

Mr. B. Mittell: Mr. Harrison has drawn attention to the various fields to which weak-current engineering is applied. I have here a gramophone of recent construction which has been designed largely on the principles that have been developed for telephone engineering and which have been applied by His Master's Voice Co. to the mechanical gramophone, chiefly through the leadership of the Western Electric Co. My particular purpose is to show the usefulness of this machine as a tone generator. In the beginning of the paper various generators—direct generators of acoustic tones—are dismissed as impracticable, but this one we find very useful for a number of measurements that do not justify the expense and complication of any kind of oscillator. Records are prepared of single frequencies, one disc

carrying 6 or 8 different tones, each separately calibrated. The response characteristic of the machine is measured and the total output from the machine is therefore known. I shall now demonstrate records of certain single frequencies. The obvious question that will be asked is how pure the tone is and what is the

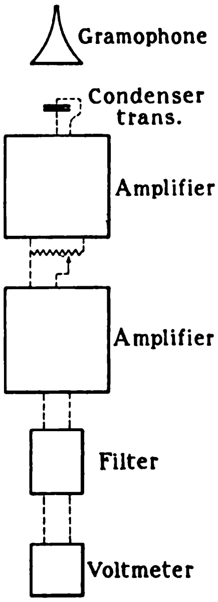


FIG. A.

good of it. No electrical frequency is pure. The authors have laid down a limit, but in the Gramophone Co.'s experience it is necessary, whatever oscillator is used, to insert a filter which will cut out harmonics. All that is necessary, therefore, is that the tone should be reasonably pure within limits, so that after the

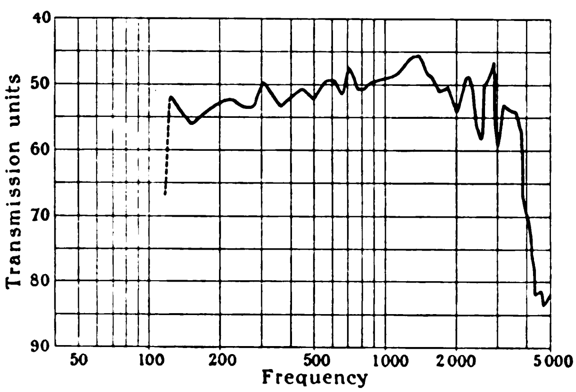


FIG. B.

harmonics are filtered out there is still a reasonable proportion of fundamental left. For several practicable purposes, routine tests of electrical equipments can satisfactorily be made with these calibrated records, without the use of a filter, by referring to a correction chart which gives the proportion of fundamental to total energy as indicated by the equipment under test. Fig. A shows the method used in calibrating the gramophone. At the top is the gramophone, and then there is the condenser transmitter—one of the Western Electric Co.'s condenser transmitters—then a preliminary amplifier and then the potentiometer which is used for bringing up the output at any frequency to a predetermined level. The voltmeter is at the bottom and at any frequency the potentiometer can be adjusted to give the same deflection on this voltmeter. It can thus be ascertained how much amplification has to be used for a particular frequency to bring it up to the standard, and a curve is plotted (see Fig. B). A filter is used to cut off all frequencies one octave higher than that being measured. The curve obtained is a good one and better than those given by the authors for the loud-speakers. I should point out, however, that whilst the curves in the paper are on a voltage scale, this curve is in transmission units plotted against a logarithmic frequency scale.

Mr. A. G. Warren: I suggest that the two curves in Figs. 26 and 27 would be greatly improved if the constants of the line per mile were included.* Towards the end of the portion of the paper dealing with the frequency characteristics of lines the authors say: "Electrical transmission lines, when their constants are known, are simple structures which lend themselves readily to calculation." Upon the usual assumptions this should be correct, but unfortunately a fair proportion of the literature upon telephony does not substantiate this statement. In the case of a continuous unloaded line the problem is quite simple, and if, say, the voltage is plotted against the length of the line, a continuous complex attenuation curve is obtained. In the case of a heavily loaded line the problem is quite simple also, because the line approximates to a filter, and the attenuation curve derives to a number of isolated points. The solution of a lightly loaded line is a more difficult matter, however, because there is a continuous attenuation variation between loading coils and then a sudden jump and this repeats over and over again. I am unaware of any published complete solution of the problem which is not open to considerable criticism from an analytical point of view. (Even the generally accepted theory of the simple unloaded line is not above question.) Admittedly calculations sufficiently accurate for existing practice are readily made, but I suggest that, in the present state of the theory, it would be unwise to rely upon calculations for cases departing widely from established practice. On page 1040 the authors describe a method of making direct tests on lines. In this connection I should like to ask them how they would make a test when the line is not sufficiently long for one to be certain that reflected waves are not reaching the measuring point. The termination of the line, of course, presents a difficulty. Any balanced circuit which is used is only an approximation, and calculations I have made suggest that any slight error in the balancing of the line may produce very considerable errors in a measurement of that type. The phasal relations of the direct and reflected waves do not lend themselves to accurate determination except at the receiving point. There they are easily determinable and it

* Since added for the *Journal*.

appears to me that a more reliable method would be to measure the current in the receiving section rather than to measure the voltage at some other point of the line. It might not give one the presumed accuracy of the other method, but one would be certain of it. It would be of assistance if the authors were to give the constants of the line for Fig. 29, and also the loading and the length of line.* In a paper accepted for publication in the *Journal*† I have shown that in a loaded line, even if there are no variations in the size of coils and so on, there must be as many dominant frequencies as there are sections. I should like to be assured that the variations which the authors show in Fig. 29 are really due to irregularities in the line, and that they are not partly due to reflections caused by imperfect balancing of the line at all frequencies. Fig. 30, again, is said to refer to a non-reactive line of line impedance of 1 000 ohms. It can, of course, if it is a real line, only have that impedance at one frequency. What was the frequency ? Then again, the authors point out that for reasons of economy it is desirable to reduce the number of loading coils to as low a value as possible. Of course, the objection to doing so is that the cut-off point is also lowered. Yet in Figs. 28 and 30 they refer to a line, which certainly does not cut off at 3 600 cycles, being used with a filter cutting off at 2 000 cycles. Had the line been designed with a small number of loading coils of greater value and wider spacing, would not line irregularities, attenuation, and cost, all have been reduced ? Fig. 31 shows an interesting case of the use of reflection in the determination of the position of a fault. For a loaded line there should be as many peaks on that curve as there are sections between the fault and the transmitting point, if the line is perfectly regular. I should like to know how far irregularities in the coils interfere with that determination. If one assumes a perfectly regular loaded, unrepeatered line with a bad value for the receiver impedance, one can get curves bearing some resemblance to Fig. 29 with most impressive irregularities, but do those irregularities mean very much ? They exist on the line up to the receiving point, but at the receiving point they almost disappear, because there the reflected wave bears a very definite relation to the transmitted wave: the relative magnitudes and phase are almost completely preserved throughout the whole frequency range. As one moves backwards from the receiving point the phase displacements become cumulative. There are, therefore, considerable current variations, with frequency, at the centre of the line, but these variations only exist in the receiver in a much smaller degree.

Mr. E. S. Ritter: Under the heading of " Apparatus for the production of electrical energy of constant value over the required range of frequency," the statement is made that " the Pollock alternator gives up to 6 000 cycles at 6 000 r.p.m." I have not worked at such a high frequency as this, and I have yet to see such high frequencies demonstrated at that speed. In Fig. 8 it is rather extraordinary that the voltage at zero frequency is apparently high, and then as the frequency increases the voltage falls and remains more or less constant. Is this really correct ? Under the heading " Frequency characteristics of lines " the authors quote a paper by Mr. G. A. Campbell which appeared in the *Philosophical Magazine* for 1903. I have looked up this reference, and I am under the impression that there is a slight error in their quotation.* They give the expression as $\frac{1}{2}\omega d\sqrt{(LC)}$, where $\omega = 2\pi \times$ frequency, $L =$ coil inductance and $d =$ distance between the coils. The term C is not explained, but it is presumably the capacity. Now, in the paper from which the authors quote, L and C are the inductance in henrys and the capacity in farads per mile of the circuit, where d is the spacing of the coils in miles. If that correction is made, the formula given in the present paper is correct. Another statement which requires qualification is with regard to four-wire repeaters, where the authors say: " With four-wire repeater circuits no repeater balances are required." That would rather imply that no balances are necessary with the four-wire repeater circuit, but as a matter of fact two balances are required at the ends of the circuit, and the gain in the circuit is to some extent limited by the accuracy of those balances. The authors say that Fig. 31 shows the input current for a 500-mile, 200-lb. aerial line, but I have not seen a 500-mile aerial line with such good characteristics. Is this a real line or an artificial one ? At the end of the Section dealing with impedance and power measurements the authors say: " It is obvious that the test made with the oscillator is very much quicker and less laborious than the corresponding tests of impedance made by means of a bridge," but I still remain to be convinced. In Fig. 26 it will be seen that the attenuation of the 20-lb. cable rises with frequency; in other words, the losses in the cable are higher as the frequency goes up. On the other hand, it will be seen from Fig. 32 (*a*) that the received voltage with the repeating coil in the cord circuit goes up with the frequency, and if the line is not too long these two effects will more or less compensate each other, and the received energy is more or less constant at different frequencies. In other words, the use of 20-lb. cable of not too great a length will tend to correct the distortion caused by the cord circuit. The same applies to Fig. 33 to some extent. Apparently if two instruments are joined up with a length of loaded cable, the frequency response levels up and the articulation is improved.

Captain F. Reid: I am chiefly interested in the application of this paper to the transmission of speech over a public telephone system. The transmission engineer has to meet three main requirements in the transmission of speech:—(1) Adequate volume; (2) elimination of distortion; and (3) transmission of a sufficiently wide frequency band. The authors, in emphasizing the importance of frequency characteristics, hitherto too much neglected, have somewhat overlooked the necessity for volume efficiency. On page 1023 they state " Articulation is a function of the perfection of reproduction of the originating wave-form." I suggest the addition of the words " but is also dependent on intensity." Figs. C and D are taken from an article by H. Fletcher in the *Bell System Technical Journal*, July 1925. Fig. C shows how articulation varies with

* Since added for the *Journal*.

† See p. 758.

* Since corrected for the *Journal*.

intensity. The ordinates show percentage articulation correctly received. The sensation level is measured in transmission units above the threshold of audibility, e.g. sensation level 40 indicates an intensity of sound which if attenuated 40 transmission units would be just inaudible. (10 transmission units are approximately equal to 11 standard miles at 800 cycles.) Fig. D shows how the sensitivity of the ear for a particular frequency varies with intensity. The lower curve,

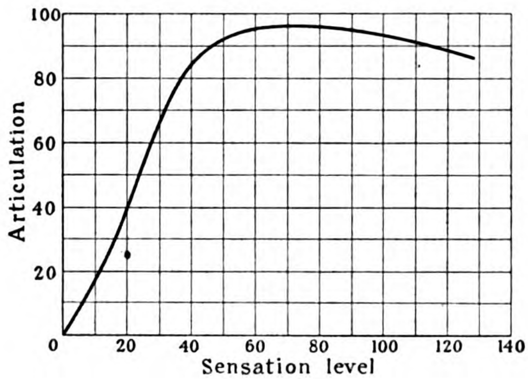


Fig. C.

which corresponds to Table 1 in the paper, represents the sensitivity to sounds which are barely audible. The ear at this intensity is most sensitive to frequencies of 1 000 to 2 000 cycles. At the other range of audition (sounds so loud as to cause discomfort) the conditions are reversed and the ear is most sensitive to very low or very high pitches. These curves show that if attention is not paid to maintaining adequate volume the

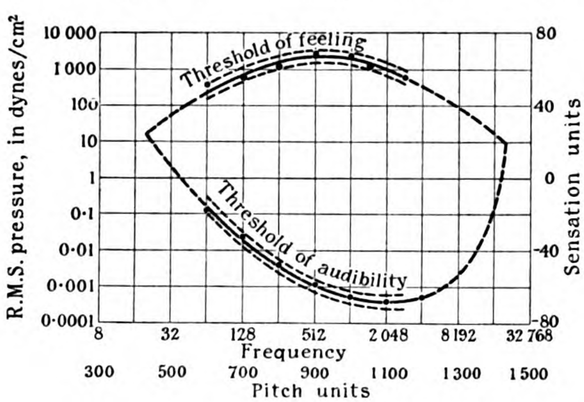


Fig. D.

ear will introduce distortion. The range of good articulation shown in Fig. C is only about 60 standard miles. This does not allow much margin for variation in lines, e.g. between a good local call and an indifferent long junction circuit, and for the difference in intensity between a man shouting close into the transmitter and a girl talking quietly away from the transmitter. One's experience of telephone testing does not seem to agree with Fig. C. The explanation lies in the elimination in commercial telephone circuits of all frequencies below 250 cycles. These low frequencies are hardly, if at all, necessary to articulation, and their presence would limit the extent to which the frequencies in the middle range, which are most essential to articulation, could be amplified in a transmitter. If all frequencies were amplified equally the low frequencies would mask those most necessary for articulation. By eliminating the low frequencies it should be possible to secure better articulation over a telephone circuit than with direct speech. I should like at this stage to comment on some of the features of the method of recording frequency characteristics adopted by the authors. (1) The record has to be taken so slowly that it represents only the steady state. All resonances have had time to build up to their full value. In transmitting speech, however, the transients are of great importance. A transmitter might give quite a flat resonance curve and yet fail to respond with sufficient rapidity to the rapid changes of wave-form occurring in speech. The authors point out on page 1024 the possibility of compensating for the frequency characteristic of one piece of apparatus by modifications in other apparatus or amplifiers. If no attention is paid to the time constant of a resonance the "correction" might conceivably be worse than useless. If, for example, a resonance in a receiver which took 0·005 sec. to build up were corrected for by a resonant shunt which had a time constant of 0·0002 sec., for very rapidly varying wave-forms the "corrected" receiver might be much worse than if no attempt had been made at compensation. (2) Although the authors are careful to employ pure sine-wave input into the apparatus under test, no test is made of the purity of output. For example, in Figs. 13 and 14 the characteristics appear to be much better than those of a receiver. What relation do the frequencies of the output bear to the frequency of the input? Is not the defect of most carbon transmitters due to "non-linear distortion," mentioned on page 1023, partly due to the restoring force on the diaphragm not being strictly proportional to displacement and partly to the variation of the resistance of the transmitter not being a linear function of the diaphragm displacement? (3) As only one frequency is applied to the apparatus at one time, any distortion due to combination tones will not be revealed. (4) The authors show the effect on a telephone receiver of holding it to the ear. What is the effect on the ear? Has not the resonating frequency of the auditory canal and eardrum been modified? If this canal and eardrum resonated normally to, say, a frequency of 2 500 should not a resonant frequency of 2 500 be introduced into the telephone system to compensate for this resonance being eliminated in the ear? In conclusion I would express the opinion that at the present stage of the telephone art it is necessary to employ the principle of resonance to obtain the necessary volume efficiency. The resonances should, of course, be made as flat as possible by damping, and any improvements which increase the volume efficiency of telephone plant will also permit increased damping. If this view is correct, then the question of the most suitable resonant frequencies should be determined. The solution lies in a study of the production and interpretation of articulate speech by the voice and ear.

Fig. E shows sections of a human ear. I would draw attention to the marked resemblance between the cochlea and the mouth. There are two main resonating cavities and the sound is introduced in each case at one end of the upper cavity. The basilar membrane (or the auditory nerve itself) corresponds to the tongue. I suggest that the interpretation of articulate speech by the ear is a signal system whereby the auditory nerves indicate the position of the tongue. In a way it is analogous to lip-reading as taught to the deaf. The sensor auditory nerves are no doubt linked to the motor nerves of the tongue, and motions of the basilar membrane are almost automatically copied by the tongue. A child learns to speak by listening to speech—not by watching the motion of a speaker's lips and tongue. Conversely the basilar membrane copies the movements of the speaker's tongue (but to a very different scale) when listening to articulate speech. This view is only a speculation, but, if correct, how would a telegraph engineer provide a signal system between the mouth of a speaker and an ear so that the motions of the membrane in the latter copy the motions of the tongue? Having only one medium he would utilize the resonant frequencies of the three chambers in the ear. We have evidence of a three-colour theory of vision, and Nature is very much inclined to solve similar problems in the same way. The resonances are probably very flat (the red sense covers almost the whole range of the visible spectrum). I am not therefore suggesting that transmitting three bands of frequencies will give as good articulation as if the whole range were transmitted. A three-colour print is not equal to natural colours, but if economy forces us to introduce resonances it is suggested that three of the resonances should be the peaks of the resonant curves for the three chambers in the cochlea.

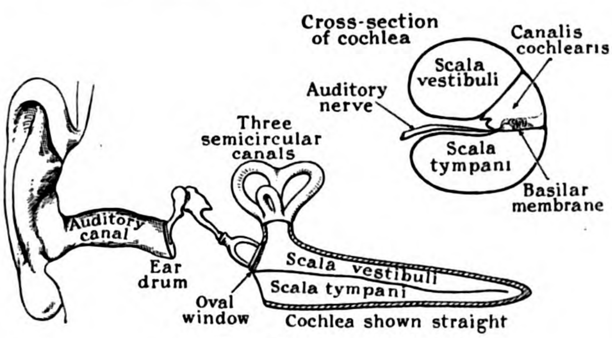


FIG. E.—The ear.

Mr. L. C. Pocock: The difficulties in the way of making such apparatus are very great. Prof. Mallett has indicated that it is not done by simply copying a circuit, and, whilst I congratulate the authors on having done it, I feel that they should have given more details of the difficulties encountered and the means by which they were overcome. Failing detailed design information, perhaps the authors would indicate whether they propose to put the apparatus on the market, and, if they do, perhaps they will consider the advisability of making the frequency scale logarithmic. It would also be more convenient if the amplitude or voltage scale were made to follow a linear instead of a square law. The peaks of the curves shown are much exaggerated, and it would be preferable if they were re-drawn on a logarithmic scale. I should be glad to know what results are obtained with the circuit shown in Fig. 2. As the authors probably know, several forms of this kind of circuit have been used on the Continent, especially in Germany.* I should like to have some further particulars of the special output transformer used. I do not quite understand from the description given in the paper how the transformer is made. Figs. 13 and 14 give some transmitter characteristics but do not really indicate what is happening over an extended frequency range, and of course the peaks are very much exaggerated by the scale; however, the curves show what is a well-known fact, namely that the telephone transmitter of to-day is far from being the best part of the apparatus in a telephone circuit. Although the solid-back transmitter used throughout this country has done extraordinarily good work I think we may reasonably expect a change and an improvement in transmitters before long. The improvement in line transmission and general line conditions has put upon telephone engineers a heavy obligation to bring the terminal instruments up to date. Under the heading "The Frequency Characteristics of Telephone Receivers" there is a short note in brackets referring to basic standard receivers. This note seems to suggest that telephone receiver standards should be used at a distance from the ear. I cannot think that a receiver standard used at a distance from the ear can have any real value. In the first place, although the resultant sound of the receiver can be affected by a variation of the position on the ear, it is also true that if the receiver is held away from the ear, another variable, namely the undefined, uncertain acoustic properties of the surrounding space, is introduced. In the second place, any fundamental receiver standard of performance is of value only under the conditions in which it really is intended to be used. Two complex sounds can be said to be equal only if the ear indicates they are equal, and the human ear is a variable factor so that equality only exists as a statistical average obtained with a large number of observers. I think it is only reasonable to include in that average the variations corresponding to variation of position of the receiver on the ear, just as much as we are bound to include the variation of the sensitivity of individual ears. Under the heading "Frequency Characteristics of Audio-Frequency Amplifiers" the authors say that intervalve transformers are tested between a resistance and a rectifying valve, and state that the plate circuit impedance may in some cases affect the result. As a matter of fact, in most cases the plate circuit impedance is the determining factor as regards the location of the point of resonance of the transformer. A number of performance tests have been made on transformers between valves loaded in different ways, and the results have been compared with calculated curves based on the transformer constants obtained by impedance analysis. It has been found that the

* See, for example, *Elektrotechnische Zeitschrift*, 1925, vol. 46, p. 915.

shape of the curves can be fully accounted for by a comparatively simple transformer theory when the load in the plate ciicuit is taken fully into consideration. I hope that the authors will now use this apparatus to produce a good deal of very necessary design data. I think there is a very real need for some sort of standardization of impedance data. There are a number of problems in which we need to know what is the average or representative terminal impedance of subscribers' lines at the subscribers' terminals, what is the average impedance of junction connecting lines or subscribers' sub-sets as measured from the exchange, and so on.

Mr. P. E. Erikson (*communicated*): In the introductory paragraph the authors refer to the two fundamental factors which are of first importance in determining the transmission efficiency of a telephone circuit, namely (1) volume and (2) articulation. If either of these factors is below a certain standard the intelligibility of the transmitted speech sounds is adversely affected. Intelligibility is here defined as the percentage of ideas correctly interpreted over a given circuit. The authors define articulation as a function of the perfection of reproduction of the originating wave-form. They also point out that badly distorted speech may be understood by an efficient co-operation of the ear and the brain of the listener. They rightly emphasize the fact that, when the context does not form an idea, such as in transmitting isolated words or sounds, the articulation requires to be at a much higher level for efficient reception. In this connection it would seem desirable to differentiate between at least two kinds of articulation—(1) "sound articulation," which may be expressed as the percentage of elemental meaningless sounds correctly received over a circuit, and (2) "syllable articulation," which is the percentage of whole syllables correctly received over a circuit. It is understood that the Post Office Research Section has done a considerable amount of work along these lines. Since quantitative articulation tests are rather laborious to carry out, it would be of interest to telephone engineers to learn the general conclusions which the authors have reached in regard to the relative value of tests carried out on the above bases. In this connection it may not be out of place to point out that articulation, as such, does not seem to be entirely adequate in rating the performance of a telephone circuit. A more satisfactory solution appears to be in terms of the time required to transmit ideas over the circuit. This conception is brought out in a recent paper * and there referred to as "traffic efficiency." The traffic efficiency of a reproducing system is there defined as being inversely proportional to the time taken to convey a single simple idea over the system. One of the authors, in discussing the paper referred to, suggests the term "transmission speed factor" for the same conception.† The latter term seems to convey the conception better, but whatever term is ultimately adopted is a matter of secondary importance. The main point is that a comprehensive rating of a circuit could be given by the ratio of the time required to transmit a set of ideas over an ideal circuit to the time required to transmit the same set of ideas over the circuit in question. Figs. 21–25 show frequency characteristics of loud-speakers—with and without horns. Presumably these characteristic curves are all based on the same volume-input level. It is noted that the curves for the horn-type loud-speakers show a lower cut-off point at, or near, 500 cycles per sec., whereas the hornless types cut off at about 250 cycles per sec. This difference in performance between horn-type and hornless loud-speakers is well known, but it may be of some interest to display it by a direct graphical comparison. For this purpose Fig. F has been prepared. This shows the frequency-response characteristics of a commercial horn loud-speaker and a hornless loud-speaker of a type described in British Patent Specifications Nos. 231556, 239245, and 240596. Apart from the more uniform response over the frequency range included, the hornless type extends down to frequencies of the order of 50 cycles per sec., whereas the horn type cuts off rather sharply at about 250 cycles per sec., the latter being due to the taper of the horn. In regard to the authors' method of portraying frequency characteristics, it is considered that for the purposes of serving as a criterion of performance, except in special cases, a frequency characteristic based on power ratios is generally more fundamental and more instructive than a frequency characteristic based on voltage ratios. Whilst, for purposes of measurement and calculation, voltage ratios are often more convenient, the conception of efficiency calls for the use of power ratios. It may be argued that the input to a valve is of so high an impedance that no power is supplied to it, but the power loss in the grid leak or in the input transformer is usually a finite quantity. The impedance of the human ear may be said to be purely reactive and to take no power, but the unavoidable coupling losses, the slip or leakage introduced between the contact of the receiver and the ear, are quantities of no small importance. In every practical case the production of alternating pressure

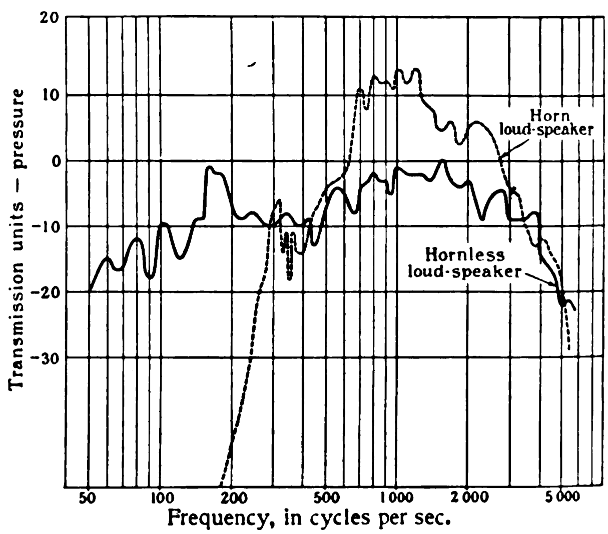


FIG. F.—Efficiencies of horn and hornless types of loud-speakers.

* L. C. Pocock: "Faithful Reproduction in Radio-Telephony," *Journal I.E.E.*, 1924, vol. 62, p. 791.
† Loc. cit., p. 808.

or voltage calls for the expenditure of power, and every problem therefore resolves itself into the question of producing this power at the required point with a minimum initial expenditure of power.

Mr. A. M. Hallawell (*communicated*): I was specially interested in that portion of the paper which deals with the employment of the Rayleigh disc, as I have recently been carrying out some experiments with the same apparatus in the research laboratories of His Master's Voice Gramophone Co. The apparatus is practically identical with that used by the authors except that I believe their disc is more sensitive than ours. I should like to suggest, first of all, that the 4 in. lining of cotton waste for the chamber is not quite as effective in reducing reflection effects as one would infer from Prof. Mallett's recent paper.* Exploring a short region about 8 cm long in front of the source at one or two frequencies is not calculated to show up standing waves very readily; if the whole of the region more remote from the source be explored, I think that the authors will find, if they have not already done so, that standing waves of quite considerable magnitude are evidenced at the higher frequencies. At lower frequencies it is difficult to detect the effects of reflection by looking for standing waves, because the box is too small to permit of their formation inside it. Nevertheless, reflection will still be disturbing the acoustic field, and I do not understand how the authors are able to gauge and allow for its effects at all frequencies. I should like to ask the authors if they were able to satisfy themselves that their telephone receiver with its resonator was producing a wave-form free from harmonics at the lower frequencies. If is of importance to be certain of this when calibrating transmitters, etc., otherwise a high response may be indicated at lower frequencies which in reality might largely be due to the transmitter's ready response to the harmonic. I have so far been unsuccessful in finding a telephone receiver which will fulfil the above conditions at reasonable outputs. Perhaps, however, the sensitivity of the authors' disc enabled them to work with very small outputs, and it would be interesting to know what was approximately the order of the sensitivity of their disc. Again, were they quite certain that the telephone-resonator combination was behaving as a source of spherical waves when radiating at low frequencies? If, as I suspect, this is not the case, it is not possible accurately to calculate the pressure or acoustic intensity from the particle velocity, since formulæ connecting these quantities are only available for the cases of plane, spherical and cylindrical waves. I cannot agree with the authors that a body such as an eddy-current transmitter placed 6 cm behind the Rayleigh disc is without important influence on the field around the latter, and I should like to know what steps they took to support such a conclusion experimentally. A question which is of importance in connection with all loud-speaker tests is: How can the characteristic of the speaker most usefully be expressed? The ideal method would be, of course, to give the overall characteristic of the speaker working in conjunction with the amplifier with which it is to be employed. Unfortunately loud-speakers are not usually supplied with their own amplifiers and hence it would seem desirable to express the frequency characteristic in such a way that it refers to the loud-speakers alone. The authors apparently interpose a high-resistance attenuator between the oscillator output transformer and the instrument under test, the voltage across the latter being measured. This procedure in itself would in many cases improve the characteristic of a loud-speaker amplifier combination, but it can hardly be said to be common practice. I think, therefore, that the acoustic output per unit current in the speaker over the whole frequency range should be given, together with its impedance-frequency characteristic. The overall performance of any given loud-speaker—amplifier assemblage can then be predicted from these curves, the performance of the amplifier being known. The authors have produced an effective and convenient form of oscillator. I am sure many are looking forward to receiving some practical hints as to how the many desirable features it possesses may be attained. The single-dial control over the whole frequency range, combined with the constant-voltage output, has made possible the autographic tracing of the frequency-characteristic curves. This is in itself an important feature, because it means that there is no possibility of the high but narrow peaks and narrow dips in the response curves being missed, as is frequently the case when a series of readings at definite frequencies are taken. It is these peaks and dips, however narrow, that play such an important part in determining the quality of reproduction.

* *Journal I.E.E.*, 1925, vol. 63, p. 502.

Mr. A. C. Timmis (*communicated*): The imperfections of the ordinary telephone transmitter and receiver are strikingly shown by the authors' curves, but the fact that the vertical scales are practically square-law scales gives a somewhat exaggerated impression. I would suggest that a really good rectifying valve, such as is now available with separately heated cathodes, would enable a fairly uniform scale to be obtained. With regard to the testing of intervalve transformers, although the method shown in Fig. 36 gives in a convenient manner a good idea of the behaviour of a transformer under various conditions, the results must be somewhat inaccurate. The impedance of the grid circuit connected to the secondary has considerable influence on the (primary) impedance of the transformer and therefore on the voltage produced across the primary. Under the usual conditions of audio-frequency amplifiers and telephone repeaters the grid impedance may be regarded as a practically pure capacity of the order of 50 $\mu\mu$F, which is of course much higher than the electrostatic capacity between the electrodes. The effect of adding a capacity of 50 $\mu\mu$F or so is shown by the curves of Fig. 37. For any ordinary valve this capacity may be calculated approximately from the formula

$$\text{Effective capacity} = C_1 + C_3 + \tfrac{1}{2}\mu C_2$$

where C_1 = grid-filament capacity,
C_3 = anode-grid capacity (both including the valve holder),
and μ = the amplification factor.

The most important quantities are μ and C_3, and it is evidently necessary, in specifying the performance of a

transformer, to state that it is tested between two valves of a particular type. In the arrangement shown in Fig. 36 a rectifying valve is used on the secondary of the transformer. Its amplification factor must vary under the conditions of test and this will give rise to errors. They are, no doubt, small, but can be eliminated by using an amplifier in front of the rectifier, so reproducing practical conditions. In the case of transformers having a turns ratio of 20 : 1 or 30 : 1, such as are used in telephone repeaters, the effect of the grid impedance (apparent capacity) is very much greater than in the case of intervalve transformers, with a turns ratio of, say, 4 : 1, and reduces the primary impedance seriously at high frequencies. For instance, a certain 25 : 1 transformer, with an L.S.5 valve connected to the secondary, had a primary impedance of 570 ohms at 2 000 cycles. Without the valve (secondary open) the primary impedance was 760 ohms at 2 000 cycles. The amplification factor of an L.S.5 valve is about 5. Another valve, with an amplification factor of 10 and about the same capacity between electrodes, reduced the impedance to 415 ohms at 2 000 cycles.

Dr. H. Salinger (*communicated*): The Rayleigh disc method has been used by the Telegraphentechnisches Reichsamt, Berlin (the work being carried out by Dr. E. Meyer), in the course of an investigation of the frequency characteristics of loud-speakers and has been found to be very convenient. The conditions were such that the sound waves were as nearly as possible plane. The calibration method was different from that described by the authors. According to a formula derived by König * and experimentally confirmed by Zernow †

$$P = a\sqrt{\left(\frac{3\rho D}{4r^3}\right)}$$

where P = R.M.S. pressure of sound in dynes per cm^2, ρ = density of air, a = velocity of sound, r = radius of the disc, and D = torque exerted on the disc by the acoustic forces. The formula assumes that the thickness of the disc is negligible in comparison with its diameter, and that the disc is located at an angle of 45° to the direction of the sound waves. In order to obtain P it is therefore sufficient to measure D. Now $D = 4\pi^2 K\alpha/T^2$, where α = observed angle of deflection, K = moment of inertia, and T = undamped oscillation period of the disc. K can be calculated, hence it is only necessary to determine T in order to convert the observed angles into sound pressures. With a disc of mica of radius 0·25 cm, hanging on a gold filament of 10 cm length and 5×10^{-4} cm diameter, T was found to be 7 seconds and $P = 0{\cdot}80\ \sqrt{n}$, where n = deflection in mm, the distance from the scale being 2 340 mm.

Messrs. E. Gerlach and **C. A. Hartmann** (*communicated*): The method suggested by the authors for the calibration of transmitters requires special means in order to eliminate sufficiently the action of stationary waves, which are produced by the reflection of the sound at the transmitter and the walls of the test-room, and, especially at the higher frequencies, give rise to annoying interferences. In the method employed in Messrs. Siemens and Halske's laboratory these precautions are not necessary. The sound impressed on the transmitter diaphragm is measured at so small a distance that the distribution of pressure between the diaphragm and the receiving portion may be regarded as uniform. The acoustic measurement itself follows closely the principles of sound-pressure compensation which have been outlined by one of us,* i.e. the receiving portion of the pressure gauge is placed in a magnetic or electric field and the sound intensities applied to the receiving portion are compensated for by electrodynamic or electrostatic forces, as may be ascertained by listening behind the receiving portion. The order of magnitude of the currents or voltages required for compensation immediately indicates the sound pressure per cm^2. Fig. G shows a pressure gauge designed for electrodynamic compensation. The transmitter (M) is applied to the sound capsule (K). At the other end of the boring (H) in the capsule, a thin strip-shaped aluminium foil (B), acting as receiving portion, is located in the homogeneous field of the magnet (Mn). The sound power is supplied at S. The soft rubber ring (G) prevents any sound from being conveyed to

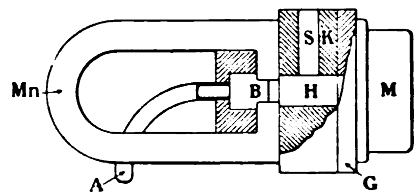


FIG. G.—Pressure gauge designed for electrodynamic compensation.

the transmitter except through the air. A current, originating in the same wave as that used for feeding the sound producer, is passed through the strip. By conveniently arranging its intensity and phase relatively to the sound phase, the strip can be brought to rest, which may be ascertained by listening at A. If B denotes the magnetic flux per cm^2, I the intensity of the strip current, and s the width of the strip, the pressure may be expressed by $p = BI/s$. Another advantage of this method, as against calibration by means of the thermophone, is that the properties of materials, excluding the dimensions of the acoustic chamber and the strip width, need not be considered in practice. The same method has also been utilized for the calibration of receivers. According to a suggestion by one of us,† the dimensions of the acoustic chamber H (see Fig. G) are made nearly equal to those of the ear-passage. By substituting for the transmitter (M) the telephone to be measured, and compensating again at B for the sound pressure, we obtain a measure for the acoustic output of the telephone applied to the ear.

Messrs. B. S. Cohen, A. J. Aldridge and **W. West** (*in reply*): In the interval between the writing of the paper and the reading before the Institution some

* *Wiedemann's Annalen*, 1891, vol. 43, p. 43.
† *Annalen der Physik*, 1908, vol. 26, p. 79.

* E. GERLACH: *Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern*, 1923, vol. 3, p. 139.
† E. GERLACH, loc. cit.

additional work was done on frequency characteristics; the results were mentioned at the meeting. In the first place, an attempt was made to obtain the frequency characteristic of a Bell receiver when acoustically loaded to correspond to working conditions, i.e. when the receiver is held to the ear. For this purpose an artificial ear was constructed which embodied an electrostatic transmitter suitable for use on the circuit shown in Fig. 2. Essentially, the transmitter comprises a disc of aluminium foil of about 1 in. effective diameter clamped to, and spaced a very small distance from, a solid back plate which comprised the back electrode. In front of the disc, and similarly spaced therefrom, was clamped a block of wood, $\frac{1}{2}$ in. thick, in the centre of which was bored a hole $\frac{3}{16}$ in. in diameter. The front of this block was covered with a layer of soft spongy rubber, about $\frac{1}{4}$ in. thick, having at its centre a piece of hard rubber about $\frac{3}{4}$ in. in diameter, in which a hole was cut tapering down to the diameter of the hole in the wood block. This design was intended to ensure that the frequency characteristic of the transmitter would not be appreciably affected by the presence of a receiver held over the aperture, with its cap in contact with the soft rubber. This artificial ear was then calibrated as a transmitter in the manner described on pages 1028 and 1029. Next, a Bell receiver was placed against the artificial ear and was actuated by the output from the heterodyne oscillator, a photographic record of the output from the electrostatic transmitter being taken. From this curve, and the calibration of the transmitter, the characteristic of the receiver was computed in terms of acoustic pressure output at the orifice of the artificial ear, per volt input to the receiver. This characteristic is reproduced in Fig. H. The receiver used was not the same as that referred to in Figs. 15 and 16, but in free air had resonances at about 750 cycles per sec. at the fundamental, and 3 300 cycles per sec. at the nodal circle mode. The degree of equivalence of conditions in the cases of a receiver being held to the artificial ear and to a real ear cannot easily be stated, especially as in the latter case the conditions vary considerably with different observers. It may be stated, however, that whereas the artificial ear alters the frequencies of resonance at the fundamental and nodal circle modes to a similar extent to a real ear, the impedance loop of a receiver at these resonances (where resistance is plotted against reactance) is smaller when the receiver is held to the artificial ear than has been found when the receiver is held to a real ear. The figures indicate, however, the very different performance of a receiver when tested in free air and when damped as in normal use.

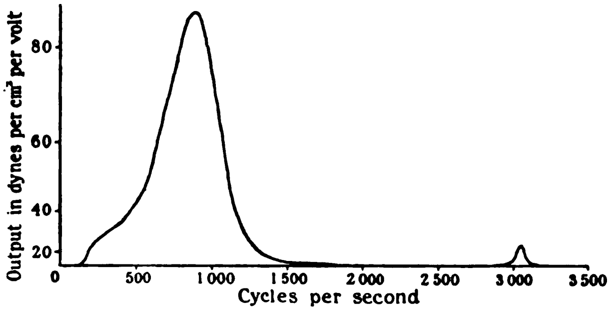


FIG. H.—Characteristic of Bell receiver held to the ear.

Another interesting characteristic is shown in Fig. J. This is the complete overall acoustic-electric-acoustic characteristic for a repeatered trunk connection with standard common-battery terminations. The lines used were artificial. As would be expected, the overall characteristic is practically a combination of the transmitter and receiver characteristics. This curve was taken with the receiver freely exposed to the air.

Several additions to the Bibliography have been suggested and this has been revised for the *Journal.*

Mr. Harrison has referred to the transmission unit and states that he believes in it. The authors are in agreement with him in this belief. This unit has, however, not been adopted by the C.C.I.,* which is the controlling organization for such questions so far as Europe is concerned, and, until this organization comes to a final decision on this matter, the Post Office must continue to use the older units.

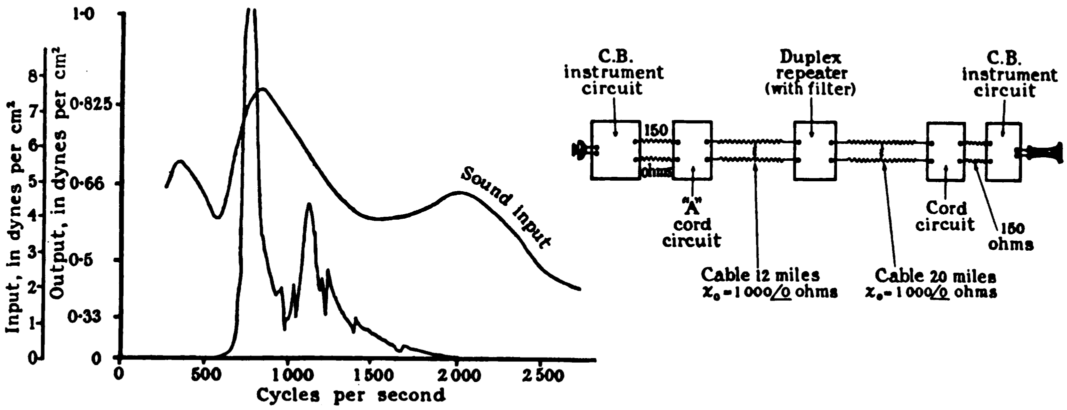


FIG. J.—Acoustic-electric-acoustic characteristic of trunk connection.

With regard to the behaviour of the telephone line

* Comité Consultativ Internationale des Communications Téléphoniques à Grande Distance.

as an electric filter, the late Mr. Shepherd, whose untimely demise we all deplore, was the first to point out that the inversion of an equivalent telephone line (i.e. series capacities and bridged inductances) gave an electric filter which had a cut-off at the lower end of the frequency scale, and he and two of the authors used such filters and combinations of upward and downward filters many years ago to investigate the relationship between articulation and frequency range.*

Prof. Mallett has suggested that all the necessary information for setting up the heterodyne oscillator is not given. It was thought that the diagram of connections and data would be sufficient, when applied with the precautions with which all users of medium- and audio-frequency apparatus are familiar, to enable satisfactory results to be obtained. There is, however, one omission: choke and condenser smoothing circuits are added in the high-tension circuits, and these, as

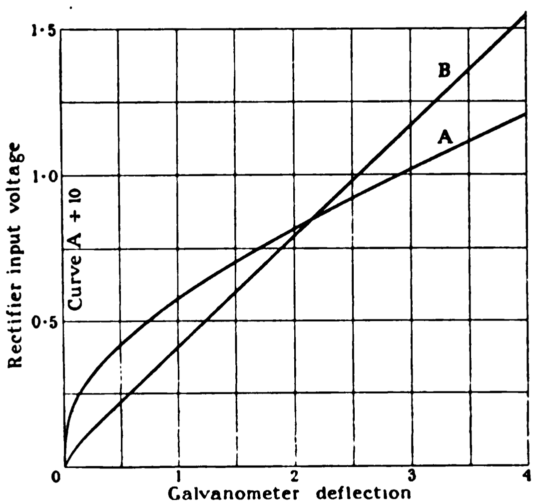


FIG. K.—Rectifier calibration curve.

A. Normal diode.
B. With 100 000 ohms in series with diode.

mentioned in the reply to Mr. Ritter, do have some effect on the output characteristic. The frequency, as required in a frequency characteristic, is given with sufficient accuracy from the readings of the variable condenser. The calibration (frequency : condenser-reading) is given in terms of the change of condenser setting from the setting corresponding to zero beat-frequency. If this zero beat-frequency is adjusted to occur at about the 10° point of the condenser, this calibration remains constant although the position of the zero beat-frequency may vary slightly with temperature and battery variations. The accuracy of the frequency value then obtained depends upon the fineness to which the condenser can be read. For individual measurements at any specified frequency the latter is measured at the time of test by means of one of the numerous types of frequency bridge available.

Prof. Mallett, and also Mr. Pocock and Mr. Timmis, refer to the false impression liable to be given in the frequency characteristics by the fact that a square-law rectifier is used. This was fully appreciated, but no other was available. Since then, however, practically a straight-line rectifier has been obtained. Fig. K shows the calibration of one of these. By using a low-impedance valve in series with a large non-inductive resistance the rectilinearity of the curve can be increased to any extent, though, of course, at the expense of sensitivity. For use with a galvanometer, however, this reduction in sensitivity need not be of great importance. The calibration curve is taken with a four-electrode valve, which type of valve lends itself well to this purpose, in series with a resistance of 100 000 ohms. Even with a straight-line rectifier the difference in amplitude between the resonance peaks and the rest of the characteristic will frequently be so great as to render advisable the taking of two records, one to show the resonance peaks and one the rest of the characteristic.

Mr. Sandeman refers to the weight of oscillators. A portable heterodyne oscillator weighing about 20 lb. (exclusive of batteries) has been designed, and it is anticipated that commercial apparatus of this type may shortly be available. He also shows that no great errors are to be expected in the frequency due to variations in temperature. This point is also referred to in the reply to Prof. Mallett. We are glad to have Mr. Sandeman's agreement with our contention that the distortion of the sound field due to the transmitter must be considered as part of the transmitter itself, but we do not agree that the effect of a man's head in distorting a sound field, when speaking to a transmitter, should be included in the transmitter characteristic. The effect requires investigation but does not appear to have the importance that the acoustic damping of the ear has on the receiver. A few characteristics have been taken with the source of sound close to the mouthpiece of the transmitter. No great difference was found in the characteristic except that the mouthpiece resonance is modified.

Mr. Mittell refers to the use of a gramophone as a source of sound. This is of interest, but appears to labour under very great disadvantages. The gramophone can only be a secondary source and requires some means of production for the original sound which produces the record. Again, elaborate electrical calibrating apparatus is required after the record is obtained. The instrument is bulky and cannot be considered as approximating to a point source, a very valuable feature. The records are made for separate single frequencies, and have not therefore the very valuable property of the heterodyne oscillator and associated apparatus in producing a continuously variable frequency. Incidentally, the instrument as demonstrated appeared to produce a noticeable hiss, and there also appeared to be a beat in the intensity.

Mr. Mittell states that no electrical frequency is pure, and that, in his experience, a filter is necessary in order to eliminate harmonics. We would point out that in no case has it been found necessary to use an electrical filter to purify the output from the heterodyne oscillator, but that, when a pure source of sound is required, use is made of an acoustic resonator from which, as pointed out by Messrs. Mallett and Dutton, a very pure note is obtainable. In obtaining the curve of Fig. B, pre-

* G. M. B. SHEPHERD: *Electrician*, 1913, vol. 71, p. 339.

sumably allowance is made for the condenser transmitter and amplifier characteristics. It is also necessary to know what percentage of the fundamental is attenuated by the filter at the different frequencies. Mr. Mittell does not state what precautions were taken to eliminate acoustic reflection effects.

In reply to Mr. Warren, particulars of the line constants for the different lines referred to in the paper have been included. We cannot agree with Mr. Warren's statements throwing doubt on the accuracy of the methods in general use by telephone engineers for calculating the transmission efficiency of lines and circuits. The statement that " Electrical transmission lines, when their constants are known, lend themselves readily to calculation " is correct, though this does not mean that the labour involved is necessarily small.

With regard to Mr. Warren's query as to the method of measurement for the case of an electrically short line, it is necessary, as explained in the paper, to make the line electrically long if it is the line attenuation only which is required to be measured. There is no difficulty in doing this for any particular frequency. It must be pointed out that there is no " attenuation constant " properly so called which can be given to a short piece of line with a few loading coils distributed in it, and this appears to be the case Mr. Warren has in mind.

With regard to the irregularities in Fig. 29, these are, as stated in the paper, due to irregularities in the cable, coils, etc. The figure gives the actual line impedances (due to whatever cause), and it is these impedances which must be sufficiently accurately balanced at the different frequencies to prevent " singing " of the repeater. No question of imperfect balancing of the artificial network can enter into the matter. The line used in Fig. 30 was an artificial line built up of non-inductive resistances to a line impedance of 1 000 ohms, and of course maintains this value at all frequencies. The reference to Figs. 28 and 30 is not clear. No line is mentioned in either case. Perhaps we may clear the matter up by explaining that Fig. 29 is given simply as an illustration of the kind of impedance variation which has to be balanced ; it has no specific relationship with Fig. 28 or Fig. 30. Fig. 30 simply shows the cut-off effect of the repeater filter. Fig. 31 is given to illustrate a method for the *location* of any fault or irregularity in an otherwise uniform line. In the case with the improper terminal impedance, quoted by Mr. Warren, the test would indicate the end of the line as the position of the irregularity. Loading coils are, of course, spaced in a line sufficiently closely to cause the irregularities in the wave transmission to be negligibly small. This test for fault location, made with a bridge, is in frequent use, and by its means the position of any irregularity in the line can be determined with considerable accuracy.

Mr. Ritter refers to the speed of the Pollock alternator. We can only say that the figure quoted was supplied by the designer. Fig. 8 is a reproduction of a photographic record. The curve actually rises steeply from zero to the peak shown and then falls. The effect is due to resonance in the high-tension battery smoothing circuit. Mr. Ritter has also pointed out that the G. A. Campbell formula is incorrectly quoted. This has been amended for the *Journal*. The line referred to in Fig. 31 was an artificial line. Mr. Ritter mentions an interesting point showing how the frequency characteristic of a cord circuit tends to neutralize the frequency characteristic of a 20-lb. cable, and this undoubtedly is of importance in improving the articulation of cable circuits.

Captain Reid quotes three desiderata for speech transmission ; of these, No. 3 is included in No. 2. He suggests an addition to the determining factor in articulation. The question of articulation is largely one of definition. Captain Reid is apparently confusing what may be considered to be an ideal definition of the articulateness of a system, with the practical testing of articulation by means of speech. Articulation *per se* is independent of volume, and it is only the intervention of the ear in commercial testing and use which causes the introduction of the volume effect. As mentioned later, we are concerned in this paper with telephonic apparatus only. We disagree entirely with Captain Reid's suggestion that articulation is improved by the elimination of the lower frequencies. It is surely obvious that a circuit which accurately transmits and reproduces the speech it receives will be perfect. Recent trials of a transmission system having an approximately flat frequency characteristic show that reproduction both as regards " naturalness " and articulation is practically perfect.

Captain Reid suggests that the method of taking records where " steady state " results only are obtained may give erroneous impressions due to the neglect of transient effects. It is agreed that a frequency characteristic will not necessarily indicate the exact performance under transient conditions. In practice, however, the acoustic transients appear to be of little importance, both for speech and for music. For example, both the eddy-current transmitter and moving-coil receiver described in the paper, being inertia-controlled instruments, would be expected to have a considerable time-lag, but they are found to give almost perfect reproduction of speech and music.

Captain Reid's suggestion that errors may be introduced if attempts are made to compensate one resonant portion by the addition of an inverse resonance, due to the fact that the time-constants of the two balancing resonances may be different, is hardly correct. It is not possible to balance out one resonance except by another of equal time-constant.

In testing transmitters the sound input was adjusted to approximate to that of speech, and any non-linear distortion produced by the transmitter must be considered a function of the transmitter. The question of the wave-form of the output therefore does not arise. As a matter of fact, unless the transmitter is overworked the non-linear distortion is small compared with the frequency distortion. The question of the effects of combination tones is answered under the reply on transients.

Captain Reid's remarks upon the ear and the effect upon this are very interesting and undoubtedly of great importance in transmission. They go, however, beyond the scope of this paper. We have attempted to show methods of measurement upon telephone

apparatus, and the behaviour of such apparatus under working conditions. If tests on the ear as well were to be included, the paper would need to have been very greatly extended. Captain Reid's "three resonance" speculation is very suggestive, and the recent production of a reliable transmission system with a flat frequency characteristic may enable this at some future time to be put to the proof.

Mr. Pocock's remarks regarding the heterodyne oscillator have been covered in the replies to Prof. Mallett and Mr. Sandeman. We consider the advantages of a logarithmic frequency scale negligible in comparison with the disadvantages. The advantage of a logarithmic scale in covering a wide range, by the crowding of the upper frequencies, is offset by the lower frequencies being unduly expanded. For example, if 50 cycles per sec. be taken as the lower limit of frequency the range, 50 to 200 cycles, a comparatively unimportant one, will occupy as much space as 500 to 2 000 cycles. For the comparatively small range of 5 000 cycles used, there seems no advantage in adopting any but a uniform scale. Further, with a logarithmic scale it is more difficult to interpolate the position of intermediate frequencies. As used with the present recording apparatus, to obtain automatically a logarithmic frequency scale would necessitate a condenser of specially shaped plates, in which case the valuable property of the constancy of calibration with small changes in the zero beat-frequency setting (see reply to Prof. Mallett) would be lost. The disadvantage of the square-law amplitude scale and the remedy have been referred to in replying to Prof. Mallett.

The condenser circuit shown in Fig. 2 has been found very useful as a receiving device for the measurement of sound. The pick-up condenser itself can be made quite small, can be used with a relatively long connecting lead, requires no polarizing battery, and, since it occurs in a high-frequency circuit, is much less liable to general induction than is the case with, for example, the eddy-current instrument. The transformer referred to by Mr. Pocock is presumably the output transformer of the heterodyne oscillator. This is constructed on a 1 in. square core of stalloy stampings. The windings consist of a number of slab coils about $\frac{1}{8}$ in. in thickness. Primary and secondary sections alternate. From 6 000 to 10 000 turns are used on the primary, and the number on the secondary is adjusted to the load. The number of turns per primary section is 2 000, and per secondary section is 500.

We do not agree with Mr. Pocock's objection to the use of standard receivers away from the ear. In the standard receiver suggested, an earcap similar to that used on commercial receivers is fitted, but instead of being screwed to the frame of the receiver it is bolted to it at some little distance by means of three distance-pieces. The earcap is thus held against the ear as usual, but the receiver diaphragm is open to the air, and the loading on it is independent of the exact position of the ear. Calibration can thus be made with the receiver open to the air, since this is the condition of use. With regard to the plate-circuit impedance in testing intervalve transformers, as stated in the paper this point has not been investigated, as the load on the transformer secondary includes in practice so many other variables in the secondary circuit, such as type of valve, primary and high-tension voltages, and wiring, for which no standard can be set. In the theory, therefore, the load on the secondary is taken to be a capacity load which is invariable over limited frequency ranges.

Mr. Erikson raises the question of articulation. It is not clear whether by "syllables" he means words or simply monosyllables forming parts of words. If the latter, there is little distinction between him and the authors. The Post Office Research Section has adopted the use of monosyllabic sounds for articulation testing, for the following reasons:—

(1) It is possible to prepare large numbers of equivalent lists of sounds without repetition.

(2) There is little risk of observers memorizing the sounds.

(3) The test of equivalent lists over the standard and non-standard circuits is considered to be the best method of obtaining the relative articulateness.

(4) The test is more easily carried out and gives a better quantitative result in a shorter time than a test involving whole sentences.

The relationship between articulation and intelligibility can be carried out once for all, though in this case, as pointed out by Captain Reid, the question of volume enters. While Mr. Erikson's "traffic efficiency" may be considered to be a very good ultimate test of a circuit, the difficulty of carrying out such a test must be enormous. With regard to the loud-speaker records, these are not necessarily at the same input level. The inputs were adjusted to give outputs within the capacity of the measuring set at the time. The characteristic given by Mr. Erikson for a hornless type of loud-speaker is of considerable interest and indicates an instrument which should give very high quality reproduction. We agree that a power ratio is the more fundamental ratio, but in the majority of cases a voltage ratio becomes practically the same thing. At the present moment the difficulties in obtaining power ratios preclude their use in many instances, for example in measurements upon the ear, or rather in obtaining acoustic power measurements which would be applicable when the measuring apparatus was replaced by the ear.

Mr. Hallawell is doubtful as to the effectiveness of cotton waste as an absorber. We have not experimented with other materials, but our tests agree with those of Messrs. Mallett and Dutton as to its effectiveness. Undoubtedly the kind of waste and method of packing affect the results. Standing waves, if present in the box, would be detected by taking readings over a range of distances, comparable with the wave-length, between source and transmitter. This cannot of course be done at lower frequencies, but for higher frequencies, above 2 000 cycles per sec. say, we have always employed this method. The values of the product r_2E have been found usually to lie within about 5 per cent of the mean figure for such tests, provided that the transmitter and its amplifier are not liable to amplitude distortion. This point is important and we have detected amplitude distortion in certain cases by observations on the product r_2E. It is also important to ensure that induction

on the transmitter, whether from the source of sound or otherwise, does not appreciably affect the readings. At lower frequencies, of course, this convenient means for detecting standing waves is not available, and it is suspected that at certain critical frequencies, dependent on the dimensions of the box, their effect is appreciable. A large number of points are usually taken at different frequencies at this end of the scale, and in all cases of tests on transmitters of the eddy-current or condenser type these have been found to lie reasonably closely on a smooth curve, such as would be expected from transmitters of this type.

We agree that the question of the wave-form of the source of sound is an important point, especially as the calculations involve frequency terms. We are, however, satisfied that the method of employing acoustic resonance to reinforce the fundamental note from a Bell receiver gives a sufficiently pure note. An exception occurs possibly at frequencies of half the fundamental and half the nodal circle frequencies of the receiver, at which the percentage of second harmonic is initially necessarily large. The sensitivity of the disc can be found from the formula on page 1029 when it is known that a unit of deflection, δ, on the scale measures 0·63 mm and that the distance from disc to scale is 80 cm.

We have not personally investigated fully the question of the equivalent point-source at low frequencies, but we were able to obtain readings on the disc at distances of 8 and 10 cm, whilst the investigations of Messrs. Mallett and Dutton show that the wave-front from a similar resonator tube is substantially spherical at a distance of 5 cm at 400 cycles per second. Further, we have observed that at distances of 6, 8 and 10 cm, at frequencies down to 200 cycles per sec., the quantity $V\Big/\sqrt{\left[\left(\frac{\omega}{rc}\right)^2+\left(\frac{1}{r}\right)^4\right]}$ is constant to within 5 per cent of the mean.

We regret that the distance between disc and eddy-current transmitter was incorrectly stated to be 6 cm in the advance copies of the paper.* The transmitter is placed at such a distance behind the disc as not to interfere with the beam of light from the galvanometer, and, as seen from Table 2, the mean distance from the source is about 25 cm, whilst the mean distance from source to disc is about 8 cm, so that the transmitter is situated about 17 or 18 cm behind the disc. Now if it be assumed that the eddy-current transmitter is a perfect reflector of sound, and if S_0 be the strength of the source of sound and S_1 the strength of the reflected sound from the eddy-current transmitter, the value of S_1/S_0 will be of the order of the ratio of the area of the eddy-current transmitter to the surface of the sphere with its centre at the source and its radius 25 cm. This is numerically about 0·025 and the distance of the disc from the eddy-current transmitter is about twice that of the disc from the source.

It is agreed that the method of test of a loud-speaker, in common with other apparatus, requires careful consideration and that the best method would be to test it in association with an amplifier. The tests which we made on loud-speakers were provisional, made chiefly to try out the use of the heterodyne oscillator and recording apparatus; but they were considered to be of sufficient interest for publication, pending more accurate and quantitative tests. It may be remarked, however, that where a loud-speaker is intended to be used in the plate circuit of a valve, an approximate equivalent circuit is available by replacing the valve by an ohmic resistance of, say, about 6 000 ohms to represent valve impedance, to which an E.M.F. may be applied.

* Since corrected for the *Journal*.

Mr. Timmis refers to the use of square-law rectifiers. This has been dealt with in the reply to Prof. Mallett. The rectifier calibration shown in Fig. K is considerably more rectilinear than that obtained with the separately-heated cathode valve, though this could of course be improved in the same way by means of an added resistance. Mr. Timmis's remarks on the grid impedance of a valve are of great interest. The difficulty of defining constants used in valve amplifiers, as commercially supplied, is considerable, since the wiring, valve constants and supply voltages all introduce variations in the load on the transformer secondary. In any case, however, where this load is more or less fixed and known, as in telephone repeaters, the circuit of Fig. 36 may still, it is considered, be used, since the rectifying-valve constants and voltages can be so chosen as to give the desired load, or an external capacity may be added across the grid to bring the total up to the required amount; and, moreover, a suitable impedance may also be inserted in the plate circuit to represent working conditions more closely. It may be added that the circuit of Fig. 36 may prove useful in obtaining approximately the impedance characteristic of the transformer primary, since, with a constant applied voltage, the voltages across R_1 and the transformer primary can be taken and the impedance computed therefrom.

Dr. Salinger's remarks on the calibration of the Rayleigh disc are very interesting, and particulars of further work carried out in the Post Office Research Laboratories, partly as a result of Dr. Salinger's suggestion, may be of interest. The use of a continuous flow of air for the calibration of the Rayleigh disc has been abandoned in favour of two other methods. The continuous-flow method can be made to give good results, as indicated by those obtained by Mallett and Dutton and ourselves. It is, however, rather cumbersome, and it is very difficult to ensure that there are no eddies in the stream, and that the velocity is uniform over the cross-section of the tube. The errors increase as the sensitivity of the suspended system is increased. Tests have been made, in the manner described by Dr. Salinger, using König's formula and calibrating the suspended system by measurements of the time of oscillation and moment of inertia. This method of obtaining the relation between deflection and velocity has been checked against another method, suggested by Mr. E. J. Barnes, in which the disc is exposed to a known particle velocity and the corresponding deflection measured. The disc and strip are enclosed in a sealed tube with windows at the lower end to admit the lantern beam, and the tube is oscillated with simple harmonic motion over a range of amplitude and velocity. The

effect is to cause the air in the tube to oscillate bodily at a known frequency and amplitude past the disc. It is found that, provided the frequencies are not such as to cause irregular motion such as resonance of the suspended system or part of it, the agreement between the two methods is within experimental error, say 1 per cent. Frequencies up to 30 cycles per sec. have been tested, and amplitudes from 0·2 mm to 2·0 mm.

Messrs. Gerlach and Hartmann have given particulars of what is evidently a very valuable method of sound measurement used in the Siemens and Halske laboratories. This method, which is a null one where the effects of a sound pressure are balanced out by means of a current adjustable in magnitude and phase, has the great advantage that no part of the apparatus is in motion at the time of balance. Work has been done in the Post Office Laboratories with this method for directly compensating the sound pressures, somewhat on the lines of the Gerlach compensation method. A moving-coil instrument similar to those referred to in the paper is used; that is to say a few turns of wire are wound on a mica cylinder and arranged to be in position in a strong annular magnetic field. The outer end of the mica cylinder is flush with the face of the magnet and closed with a wooden disc. Into the centre of the end of the magnetic core is screwed the stem of a standard-pattern common-battery transmitter button. The front electrode of this button is attached to the inside of the wooden disc closing the mica cylinder. The cylinder and coil are thus held in position by the microphone button only. When any sound falls upon the wooden disc the coil is moved, and an indication of this is obtained by listening on a circuit connected with the microphone button. Current of adjustable amplitude and phase is now passed through the moving-coil winding and adjusted until no sound is heard in the microphone circuit. Calibration is carried out very simply by hanging the coil, without the microphone button, in the annular magnetic field, and weighing, by means of a chemical balance, the effect of various currents in the moving coil.

LOW-FREQUENCY INTERVALVE TRANSFORMERS.

By P. W. WILLANS, M.A.

(*Paper first received* 1*st February, and in final form* 19*th July*, 1926 ; *read before the* WIRELESS SECTION 2*nd June*, 1926.)

SUMMARY.

The theoretical expression for the voltage amplification of a valve followed by a transformer is developed in its simplest possible terms, and various particular cases are considered. The importance of low leakage inductance for the uniform amplification of the higher frequencies is emphasized.

A practical verification of the theory is provided by actual measurements of the vector amplification ratio and comparisons with the theoretical equations, and graphical methods are given whereby the constants of a transformer can be deduced from these measurements and the amplification ratio extrapolated to frequencies beyond the range of convenient measurement.

A practical design of transformer is described in which low leakage inductance and self-capacity are ensured by a sectionalized and spaced construction, and a curve of amplification of this transformer is given.

Various questions relating to intervalve transformers are briefly considered, and circuits are described for increasing the amplification of low frequencies and the effective step-up ratio of the transformer.

The use of low-frequency reaction for correcting distortion is described and is illustrated by measurements.

INTRODUCTION.

The subject of low-frequency intervalve transformers is one which has excited considerable interest among radio engineers since the inception of broadcasting. The general principles on which voltage amplifiers operate have been known for a considerable length of time, but the special problem of designing a transformer to operate in conjunction with a valve so as to constitute a uniform voltage amplifier over the important range of audio frequencies has not until recently been adequately dealt with in any published work.

The paper by Mr. D. W. Dye * published in the autumn of 1924 represents a comprehensive survey of the whole problem. The author's only reasons for presenting the present paper are first that the method of measurement employed by him throughout the work is possibly novel, and, secondly, that there are some aspects of the problem of designing an intervalve transformer which it is thought might be of some interest to bring forward. If the present paper to some extent has a tendency to traverse old ground, the author can only say in extenuation that his work was carried out in 1923 for the Marconiphone Co. and, had it not been for commercial reasons, publication would have taken place some considerable time ago.

Apart from Mr. Dye's paper, the author can lay claim to no very thorough knowledge of the bibliography of the subject. A paper † by Mr. N. L. Casper summarized the intervalve transformer problem very fairly, but did not deal with it thoroughly from the mathematical point of view. The present author made a brief reference to the effect of magnetic leakage in intervalve transformers in the course of the discussion * on Mr. L. C. Pocock's paper in 1924, and also described and demonstrated a testing set for intervalve transformer measurements at the discussion † on Mr. H. A. Thomas's paper.

* *Experimental Wireless*, 1924, vol. 1, p. 691.
† *Journal of the American Institute of Electrical Engineers*, 1924, vol 43, p. 196.

The object of the present paper is to set out briefly the important theoretical aspects of the problem, to give an experimental verification of the theory and, finally, to discuss questions of design and to describe a particular form of transformer which has been patented.

The author would like to place on record at this juncture his great indebtedness to his assistant and co-patentee, Mr. M. Ward, B.Sc., who took most of the original measurements of amplification and to whose painstaking efforts in this respect any success that may have been achieved in respect of transformer design is largely due.

THEORETICAL CONSIDERATIONS.

It is not proposed to go deeply into transformer theory in this paper, but rather to develop the simplest

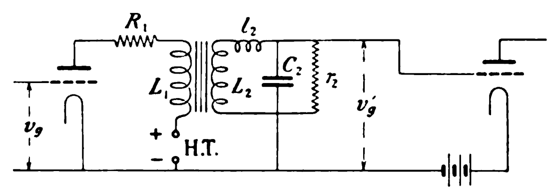


FIG. 1.

v_g = input sinusoidal voltage.
v_g' = output sinusoidal voltage.
V_g, V_g' = corresponding peak values.
R_1 = primary resistance.
L_1 = primary inductance.
L_2 = secondary close-coupled inductance.
l_2 = secondary leakage inductance.
r_2 = secondary effective resistance (shunt).
C_2 = secondary effective capacity.
m = valve magnification factor.
r_a = valve internal resistance.

possible mathematical expressions that will account for those facts which are relevant to the practical problems of design. The simplifications that have been introduced are mainly justified by experiment, though the latter was in some cases insufficient to separate out all the variables.

In Fig. 1 is shown the representation of an intervalve transformer which has been adopted as the most practical for interpreting the experimental results. The arrangement of the transformer in association with its valve also brings out clearly what is meant by a stage of voltage amplification.

Referring to the figure, a sinusoidal voltage v_g is

* *Journal I.E.E.*, 1924, vol. 62, p. 809.
† *Ibid.*, 1926, vol. 64, p. 269.

applied between the grid and filament of a valve in the anode circuit of which is connected the primary winding of the transformer. The secondary winding is connected at one end to the filament of this valve and at the other to the grid of a second valve; in the actual measurements the grid-bias battery was connected as shown, though from the theoretical point of view its exact position is of course unimportant, the filaments of the valves being in effect connected together. The voltage across the secondary winding is denoted by v_g', and the ratio v_g'/v_g, in general a complex quantity, may be termed the "amplification factor" of the stage.

The performance of the transformer may be judged in terms of v_g'/v_g, which is a function of the constants of the transformer and the angular frequency of the applied voltage. This ratio can be both calculated and measured, and a comparison between theory and experiment in this respect has formed the basis of the work here described.

The secondary inductance of the transformer is shown as consisting of two parts L_2 and l_2, the former being supposed tightly coupled to the primary and the latter completely independent of it. It can be readily shown that, so far as magnetic leakage is concerned, there is no more general way of representing an intervalve transformer, and that the location of the leakage inductance entirely in the secondary comes to the same thing as distributing it between the two windings in any proportion. In fact, in most of the transformers which were tested the greater part of the leakage inductance was located in the secondary, so the diagram is in any case in close agreement with facts.

The main assumptions are the representation of the self-capacity by a condenser across the secondary and the representation of the transformer losses by a shunt resistance across this condenser.

The former assumption is not strictly in accordance with the experimental facts, as a reversal of one or other of the transformer windings produces a change in the value of C_2. This shows that the mutual capacity between primary and secondary constitutes an appreciable part of the transformer capacity. However, if the effect of mutual capacity be strictly taken into account we have to consider a system having two natural frequencies, and, in view of the fact that the second of these is well above the limit of practical audibility, the complexity is not warranted from the point of view of interpreting the results.

In respect of the resistance it will be noted from the figure that the ohmic resistance of the primary winding is simply in series with the valve internal resistance. Apart from this the experimental evidence is that there is a loss which can be represented as a shunt across one or other winding; the reason for choosing the secondary is simply that the loads due to the valve and transformer losses respectively are indicated as being on opposite sides of the leakage inductance. It does not appear to be of importance to inquire more closely where these losses are located, as in actual practice the damping of a transformer by the associated valve when a reasonably flat characteristic is attained is very much greater than the damping due to losses in the transformer itself; it is only when additional damping resistances are applied to a transformer that an effect of any importance is obtained.

For convenience of calculation we may still further simplify Fig. 1 as shown in Fig. 2. Here we make use of the fact that the voltage across L_1 must be in a constant ratio to that across L_2, and consequently we can transfer the whole load from the secondary to the primary in accordance with well-known transformer theory. Further, the primary ohmic resistance can be absorbed into the valve resistance and counted as part of it, and thus when the symbol r_a is used it will be understood to denote $r_a + R_1$.

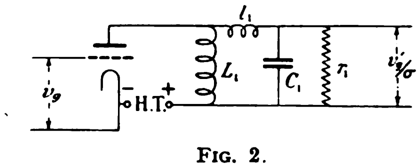


FIG. 2.

If σ = step-up ratio:—

$$l_1 = \frac{1}{\sigma^2} l_2$$
$$C_1 = \sigma^2 C_2$$
$$r_1 = \frac{1}{\sigma^2} r_2$$

voltage across $r_1 = \dfrac{v_g'}{\sigma}$

Referring, then, to Fig. 2, if we denote the anode circuit impedance by Z and the alternating voltage across it by v_a we have, from well-known theory,

$$-\frac{v_a}{v_g} = \frac{m}{1+(r_a/Z)}$$

and, from the figure,

$$\frac{\dfrac{1}{j\omega C_1 + (1/r_1)}}{j\omega l_1 + \dfrac{1}{j\omega C_1 + (1/r_1)}} = \frac{\dfrac{1}{\sigma} v_g'}{v_a}$$

Hence

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{[1 + (r_a/Z)][1 + j\omega l_1\{j\omega C_1 + (1/r_1)\}]}$$

Further,

$$\frac{1}{Z} = \frac{1}{j\omega L_1} + \frac{j\omega C_1 + (1/r_1)}{1 + j\omega l_1[j\omega C_1 + (1/r_1)]}$$

This gives

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1+j\omega l_1\left(j\omega C_1+\dfrac{1}{r_1}\right) + r_a\left[\left(j\omega C_1+\dfrac{1}{r_1}\right)\left(1+\dfrac{l_1}{L_1}\right)+\dfrac{1}{j\omega L_1}\right]}$$

If we neglect l_1/L_1 in comparison with unity and substitute for C_1, L_1, l_1, and r_1 in terms of C_2, etc., this reduces to

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1+\dfrac{r_a\sigma^2}{r_2}-\omega^2 l_2 C_2+jr_a\sigma^2\left[\omega\left(C_2+\dfrac{l_2}{r_2 r_a\sigma^2}\right)-\dfrac{1}{\omega L_2}\right]} \quad (1)$$

This equation gives a sufficiently general expression for v_g'/v_g to account for the results obtained in the case of practical transformers. It will be noted that the denominator consists of a real term having the form $A - B\omega^2$ and an imaginary term $j[C\omega - D/\omega)]$; that this is in close agreement with the experimental results will be shown later in the paper.

Special cases. Close-coupled transformers.—Assuming for the moment that equation (1) gives a tolerably good account of the properties of an intervalve transformer, it is now worth while to consider what should be aimed at in the matter of design. For this purpose we will consider the simplest cases first and then go on to the general result.

Case (1). *Loss-free close-coupled transformer.*—If we write $l_2 = 1/r_2 = 0$ in equation (1) we have the ideal case of the loss-free close-coupled transformer. The equation may then be re-written in the form

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1 + jr_a\sigma^2[\omega C_2 - (1/\omega L_2)]} \quad . \quad . \quad (2)$$

An inspection of this equation shows at once that the maximum amplification occurs, as would be expected, at the frequency for which $L_2C_2\omega^2 = 1$ and that its value is then equal to $m\sigma$. The degree of sharpness of this maximum may be best considered on the following basis. The imaginary term is numerically less than $r_a\sigma^2/(L_2\omega)$ at frequencies below resonance, but approximates to this value the lower the frequency; similarly the imaginary term is less than, but tends to reach, the value $r_a\sigma^2C_2\omega$ at frequencies above resonance. Hence, if we can make $r_a\sigma^2/(L_2)$ and $r_a\sigma^2C_2$ sufficiently small we can attain any degree of constancy desired.

Now L_2 and C_2 are characteristics of the secondary of the transformer (if we neglect the dependence of C_2 on mutual capacity as an approximation). Consequently, when once we have built a transformer of the highest possible L_2 and the lowest possible C_2, we have done our best as far as the design of the secondary winding is concerned, and it only remains to adjust the value of σ to give the required degree of constancy. It thus appears at once that if we consider a valve of given internal resistance, an n-fold increase in L_2 and $1/C_2$ will enable us to effect a $\sqrt{n}$-fold increase in σ (and consequently in the amplification) without loss of uniformity.

We may look at this problem from another angle. Supposing r_a, L_2 and C_2 are all fixed, then by a variation of σ we can obtain families of different resonance curves. If we write $\omega_0 = 1/(\sqrt{L_2C_2})$ and $b_2 = \sqrt{(L_2/C_2)}$ equation (2) may be re-written in the form

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1 + j\dfrac{r_a\sigma^2}{b_2}\left(\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}\right)}$$

or, writing ψ for $\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}$

$$-\frac{v_g'}{v_g} = \frac{mr_a}{1 + j\dfrac{r_a\sigma^2}{b_2}\psi} \quad . \quad . \quad . \quad . \quad (3)$$

The function ψ vanishes when $\omega = \omega_0$ and has numerically equal values when $\omega = \omega_0 n$ and ω_0/n, n having any value. Hence, if a resonance curve (v_g'/v_g against ω) be plotted in which the frequency scale is logarithmic, it will be symmetrical about the $\omega = \omega_0$ axis.

If a family of such resonance curves be drawn they will intersect each other, and for every value of ψ there is a value of σ giving optimum amplification. For values of ψ near $\omega = \omega_0$ the value of σ becomes increasingly large, though actually the losses of the transformer would prove a limiting factor. If σ be adjusted to give optimum amplification for a certain value of ω remote from ω_0, a reduction of σ will decrease the amplification within these limits and increase it outside them.

Hence a reduction in the value of σ flattens the resonance curve both by increasing the amplification on the extreme frequencies and decreasing it on the middle frequencies.

It thus appears (cf. Dye's paper) that the simple resonance of inductance and capacity in the secondary circuit is accompanied by no sudden changes in the amplification ratio of the combination of transformer and valve, and, in the absence of magnetic leakage, the resonance curve can be flattened to any desired extent by a sufficient reduction of σ.

Case (2). *Effect of damping on close-coupled transformers.*—Let us next consider the effect of a damping resistance r_2, magnetic leakage being still supposed absent. Instead of equation (3) we then have

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1 + (r_a\sigma^2/r_2) + j(r_a\sigma^2/b_2)\psi} \quad . \quad . \quad (4)$$

It thus appears that a symmetrical curve of the same type as before is obtained, but that the maximum amplification is reduced by the presence of the damping resistance.

To form an estimate of the extent of this reduction and the consequent change in shape of the resonance curve, let us suppose a loss-free transformer of ratio σ' to be constructed so as to have the same shape of curve as the above; then by comparison with (3) we should have

$$\frac{r_a(\sigma')^2}{b_2} = \frac{r_a\sigma/b_2}{1 + (r_a\sigma^2/r_2)} \quad . \quad . \quad . \quad . \quad (5)$$

Also since the maximum amplifications are respectively $m\sigma'$ and $\dfrac{m\sigma}{1 + (r_a\sigma^2/r_2)}$ their ratio is

$$\frac{\sigma'/\sigma}{1 + (r_a\sigma^2/r_2)} = \frac{\sigma}{\sigma'}, \text{ from (5)}$$

Hence the maximum amplification in the transformer of ratio σ' is σ/σ' times that of the transformer of higher ratio σ when the latter is damped down by a resistance across the secondary so as to give the same curve as the former.

Effect of magnetic leakage.—Let us now consider the effect of leakage. We see on reference to equation (1) that the presence of l_2 has two distinct effects: (a) a change in the real term in the denominator which is

now no longer constant but has the form $A - B\omega^2$, and (*b*) a change in the imaginary term amounting to a virtual increase in the self-capacity of the transformer. The former effect is manifested whether the transformer has appreciable losses or not; the latter only occurs when there are losses as well as magnetic leakage.

Case (3). *Transformer with magnetic leakage but no losses.*—In practical cases the effect of r_2 is not very great except when damping resistances are applied to the secondary of the transformer. Considering r_2 as infinite, in the first place the equation becomes

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1 - \omega^2 l_2 C_2 + j r_a \sigma^2\left(\omega C_2 - \dfrac{1}{\omega L_2}\right)} \quad . \quad (6)$$

If we denote $1 - \omega^2 L_2 C_2$ by X and $r_a\sigma^2[\omega C_2 - (1/\omega L_2)]$ by Y it is clear that as ω increases from ω_0 to higher values X decreases and Y increases. Since

$$\frac{V_g'}{V_g} = \frac{m\sigma}{\sqrt{(X^2 + Y^2)}}$$

the result at first sight may either be an increase of V_g'/V_g or a decrease according to circumstances. Both effects are found under practical conditions.

In order to discriminate between the two cases we may evaluate the denominator. We have

$$\sqrt{(X^2 + Y^2)} = \sqrt{\left\{\begin{matrix} 1 - 2r_a^2\sigma^4(C_2/L_2) + \omega^2(r_a^2 C_2^2\sigma^4 - 2l_2C_2) \\ + \omega^4 l_2^2 C_2^2 + r_a^2\sigma^4/(\omega^2 L_2^2) \end{matrix}\right\}} \quad . \quad (7)$$

The first two terms are constant and, provided l_2 is sufficiently small and L_2 sufficiently large, the last two may be neglected over a considerable range of frequencies above ω_0. The criterion for discriminating between a rising or falling characteristic is thus whether $2l_2/C_2 >$ or $< r_a^2\sigma^4$.

We have, therefore, as an approximate result for low values of leakage, that if $r_a^2\sigma^4 < 2l_2/C_2$ the characteristic will rise for frequencies above ω_0 and that if $r_a^2\sigma^4 > 2l_2/C_2$ it will fall.

The result of this effect is that we can no longer flatten our characteristic indefinitely by reducing the value of σ, because otherwise it will rise at the higher frequencies. There is thus a limit to the uniformity of amplification obtainable in any transformer unless damping resistances be employed in the secondary circuit.

Case (4). *Transformer with both losses and leakage.*—Returning again to equation (1) we see that in the general case

$$X = 1 + \frac{r_a\sigma^2}{r_2} - \omega^2 l_2 C_2$$

and $$Y = r_a\sigma^2\left[\omega\left(C_2 + \frac{l_2}{r_2 r_a \sigma^2}\right) - \frac{1}{\omega L_2}\right]$$

and the criterion for a rising characteristic is

$$2l_2C_2\left(1 + \frac{r_a\sigma^2}{r_2}\right) > r_a^2\sigma^4\left(C_2 + \frac{l_2}{r_2 r_a\sigma^2}\right)^2$$

which reduces to

$$2\frac{l_2}{C_2} > r_a^2\sigma^4 + \frac{l_2^2}{r_2^2 C_2^2}$$

Thus it is evident that in all cases the tendency of the characteristic to rise at high frequencies is diminished by the presence of the damping resistance. At the same time the proportionate amplification on the low frequencies is improved.

The objections to this method (which is in general use) of correcting the effects of magnetic leakage are two-fold. First, as has already been pointed out, the use of a damping resistance impairs the efficiency of the transformer, that is to say the flattening of the curve is only effected at the expense of a considerable sacrifice of amplification. Secondly, the effective increase in C_2 by the amount $l_2/(r_2 r_a\sigma^2)$ produces a diminution in amplification at high frequencies, so that the advantages of a damping resistance are not fully obtained, even though a sacrifice of efficiency has been made.

Referring to equation (7), if the condition for a flat characteristic is satisfied the coefficient of ω^2 vanishes and the efficiency at high frequencies is governed by the coefficient of ω^4, namely $l_2^2C_2^2$. Accordingly, in order to attain uniformity of amplification up to the highest possible frequency, we must keep l_2C_2 as small as possible. In other words, whereas by a suitable choice of step-up ratio we can ensure a flat characteristic to a transformer over a limited range, the upper limit of this range is determined by the degree of constancy of X.

If a damping resistance is employed we enable X to be kept constant to a greater degree, but at the expense of efficiency. If, on the other hand, we reduce the leakage inductance we attain this constancy with only the small sacrifice of efficiency necessitated in order to preserve the flat characteristic.

It is interesting to work out how much loss of amplification is involved in producing, by means of a damping resistance applied to the secondary of a transformer, the same constancy of X as results from a specified reduction of l_2, say to one-quarter of its original value.

Referring to equation (6), if we reduce l_2 to $\frac{1}{4}l_2$ we have

$$-\frac{v_g'}{v_g} = \frac{m\sigma}{1 - \frac{1}{4}\omega^2 l_2 C_2 + j r_a\sigma^2\left(\omega C_2 - \dfrac{1}{\omega L_2}\right)}$$

whereas if we apply a damping resistance r_2 to the secondary and increase the step-up ratio to σ' (the value to be settled by a comparison with the above) we get

$$-\frac{v_g'}{v_g} = \frac{m\sigma'}{1 + \dfrac{r_a(\sigma')^2}{r_2} - \omega^2 l_2 C_2 + j r_a \sigma'^2\left(\omega C_2' - \dfrac{1}{\omega L_2}\right)}$$

[C_2' being greater than C_2, cf. equation (1)]

Now if the real terms in the denominators of the above have the same degree of constancy we must have $1 + [r_a(\sigma')^2/r_2] = 4$. Hence the real term in the damped transformer has four times the value of that in the undamped one; consequently, to keep the two curves the same shape at low frequencies we can increase the imaginary term to the same extent. Thus $\sigma' = 2\sigma$ and the maximum amplification of the second transformer

is half that of the first. If we aim at keeping the shape of the curves the same at high frequencies, σ' must be less than 2σ and the efficiency of the damped transformer is still lower.

Summary of Theoretical Considerations.

The conclusions to be drawn from the foregoing theoretical discussion of the problem may be summarized as follows :—

(i) The performance of a single-stage transformer amplifier may be expressed as a vector voltage amplification ratio consisting of a fraction having a numerator independent of the frequency and a denominator consisting of a real part X and an imaginary part Y, both in general varying with the frequency.

(ii) The imaginary term Y vanishes for a certain frequency (the resonant frequency) which is determined mainly by the inductance L_2 and capacity C_2 of the secondary winding. The extent of the variation on either side of this frequency is determined by the ratio C_2/L_2, the step-up ratio σ and the valve resistance r_a, the constancy being greater the smaller the values of these quantities. The values of Y are identical for any two frequencies bearing inverse ratios to the resonant frequency. As far as the design of the transformer is concerned it is of importance that C_2 and $1/L_2$ should be separately made as small as possible. The value of σ can then be adjusted in conformity with r_a so that the required degree of constancy of Y is attained.

(iii) The real term X vanishes for a certain frequency which is dependent upon the secondary leakage inductance l_2, capacity C_2 and resistance r_2. The variation of X at frequencies higher than this critical frequency is very steep, but its value tends to constancy at low frequency. The lower the values of l_2, C_2 and r_2 the higher is the frequency for which X vanishes, but a low value of r_2 impairs the efficiency of the transformer.

(iv) Since the constancy of X is not governed by σ we cannot ensure constant amplification by a reduction in ratio. The best that can be achieved is the adjustment of σ until $(X^2 + Y^2)$ is constant over a band of frequencies, but the width of this band is determined by the degree of constancy which has been achieved for X.

(v) Setting aside the alternative of applying a damping resistance to the transformer windings, the problem of intervalve transformer design therefore resolves itself into increasing the secondary inductance to the utmost extent and at the same time reducing to the lowest limits the secondary capacity and the secondary leakage inductance. This will necessitate a determination of the winding space occupied by the primary winding but not of the number of turns with which this space is filled.

We are then left with the value of the step-up ratio at our disposal and we are enabled to adjust this so that in conjunction with any given valve, and, within limits, operating into any given impedance, a voltage-amplification characteristic will be obtained of the greatest possible constancy.

Experimental Results.

(1) *Method of measurement.*—The method adopted for measuring the ratio v_g/v_i for an intervalve transformer connected to a valve has already been described in the *Journal*,* but a diagram of the apparatus employed is here reproduced for the sake of convenience (Fig. 3). During the earlier part of the work a slightly different arrangement was used in respect of the Wagner connection and for frequency measurement, but as these points do not affect the essential features of the device it is sufficient to refer briefly to the main characteristics of the apparatus previously described.

The principle of the bridge was given in the description referred to. In order to make the various operations

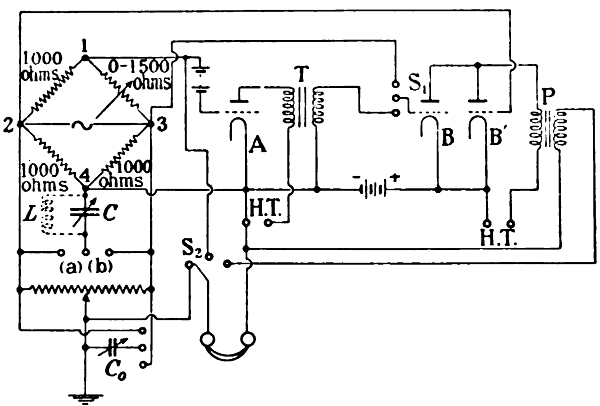


Fig. 3.

clear, simplified diagrams are given in Figs. 4, 5 and 6 which show the successive operations required to effect a measurement of amplification.

In Fig. 4 is shown the bridge set up as a frequency meter. In this case the valves A, B and B_1 are not in use and the instrument operates as an ordinary a.c. bridge. It will be seen from the diagram that a rejector

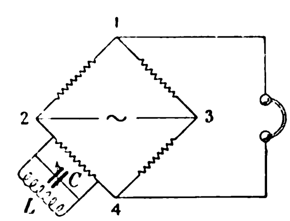


Fig. 4.—Bridge set for frequency measurement.

circuit LC is shunted across one arm of the bridge, which therefore balances at the frequency for which the reactance of this circuit is zero.

No attempt was made to determine the value of the frequency from the settings of L and C, but the apparatus was calibrated from an oscillator having a large number of harmonics, the fundamental of which was adjusted by means of a tuning fork.

In effecting the measurement of frequency the switch S_2 (see Fig. 3) is set in the central position first and a rough balance obtained. It is then set in the left-hand position, giving the arrangement shown in Fig. 4 *a*, the condenser C_0 being connected either as shown or in the position indicated by the dotted lines.

* *Journal I.E.E.*, 1926, vol. 64, p. 270.

The earth balance according to the Wagner principle is then obtained, after which the adjustment is completed according to Fig. 4.

In view of the somewhat complicated operation of setting up the source for any given frequency, it is easier to employ standard tuning forks when an arbitrary known frequency is all that is required. This has been done in most of the more recent measurements, since the agreement between theory and experiment is close enough to permit of satisfactory interpolation.

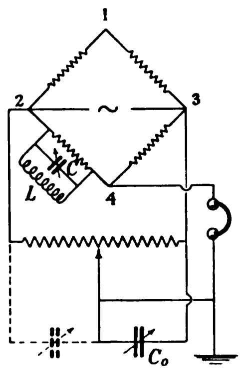


FIG. 4 *a*.—Wagner adjustment of frequency bridge.

Having set up the source of alternating current to any required frequency, the next step is to balance the two valves B and B_1. The arrangement for this is put into operation by setting the switches S_1 and S_2 of Fig. 3 in the upper and right-hand positions respectively. The resulting circuit arrangement is shown in simplified form in Fig. 5.

The bridge is balanced exactly, the variable condenser being disconnected, and the filament brightness of one

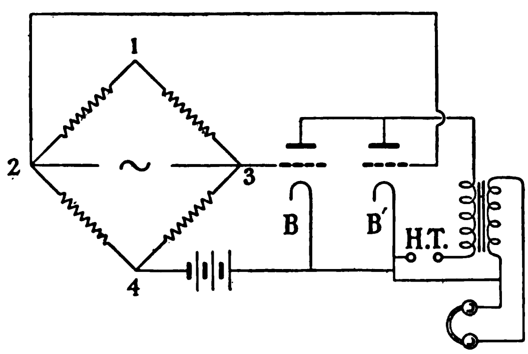


FIG. 5.—Balancing of valves B and B′.

or other of the valves B and B_1 varied until an extinction is obtained. The Wagner balance is then effected and the measurement completed as before.

The last operation, which is the actual measurement of amplification, is carried out as shown in Fig. 6, the switches S_1 and S_2 being in the lower and right-hand positions respectively. In this case we have to displace the balance of the bridge, by means of the variable resistance R_1 and the condenser C connected across one or other of the two ratio arms, in order that the output voltage across the secondary of the transformer T may be equal and opposite to the voltage across 2, 4. This point is of course indicated by an extinction of the sound in the telephones. The measurement is completed as before by first adjusting the earth bridge and then re-balancing the arrangement shown in the figure.

The voltage amplification factor is equal and opposite to the ratio of the voltage across the arm 2, 4 to that across 1, 4, this ratio being readily calculable. The values of this factor are respectively given by

$$-\frac{v_g'}{v_g} = \frac{R' + R}{R' - R - j\omega R^2 C}$$

and
$$-\frac{v_g'}{v_g} = \frac{R' + R}{R' - R + \omega^2 R^3 C^2 + j\omega R^2 C}$$

according as to whether the condenser switch is in position (*a*) or position (*b*).

It is thus apparent that the measurement of amplification can be effected in a way which makes a comparison with the theoretical expression given in equation (1) a very simple matter.

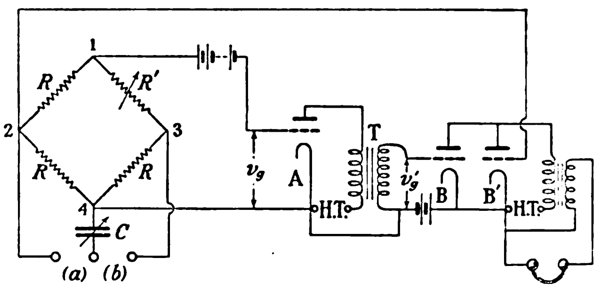


FIG. 6.—Measurement of amplification.

For this purpose it is convenient to reduce the calculated results to the form

$$-\frac{v_g'}{v_g} = \frac{1}{P + jQ}$$

and we thus have

$$Q = \pm \frac{\omega R^2 C}{R' + R}$$

and
$$P = \frac{R' - R + \omega^2 R^3 C^2}{R' + R} \quad \text{or} \quad \frac{R' - R}{R' + R}$$

according to the position of the switch.

P and Q are thus readily calculable from the settings of the bridge when a balance is obtained in the manner already described.

If it is desired to calculate the scalar amplification factor and phase angle, we have at once from the above

$$\frac{V_g'}{V_g} = \frac{1}{\sqrt{(P^2 + Q^2)}} \quad \text{and} \quad \tan\phi = \frac{Q}{P}$$

V_g and V_g' being the moduli of the corresponding voltages and ϕ the phase angle between them.

(2) *Verification of theory.*—During the course of the work a large number of transformers were tested, some of which were practical audio-frequency intervalve transformers actually on the market, others tentative designs and others again actual samples drawn from production of the final design of transformer which was adopted by the author's firm. As would naturally be expected, the measurements yielded an enormous

diversity of response characteristics, but in all cases the same general results were obtained and confirmed the theory set out in the first part of this paper.

For the purpose of this verification, and as a routine check on the accuracy of the measurements, a graphical method has been adopted which has many convenient features.

Referring to equation (1), it was noted that the expressions denoted by X and Y are functions of the frequency, having the forms $A - B\omega^2$ and $(C/\omega) - D\omega$ respectively. In other words, X and $Y\omega$ are linear functions of the square of the frequency.

If, therefore, the theory is substantially correct the expressions P and $Q\omega$ should similarly be linear functions of ω^2, and this fact can easily be checked by plotting the values of these expressions in such a manner that they should lie in a straight line.

In practice it has been found most convenient to employ squared paper in which the abscissæ are plotted according to a quadratic law and designated as frequencies, the latter being expressed, for purposes of arithmetical convenience, as kilocycles. In this case, if f is the frequency in kilocycles corresponding to any observations, all that is necessary is to plot the values of P and Qf as ordinates against the corresponding frequencies, and the results should, and in fact very largely do, lie on a straight line.

In cases where the results conform closely to theory it is readily possible to obtain empirical formulæ for P and Qf, and by means of these to obtain a general formula for the voltage amplification of the stage, which will enable extrapolation to be carried out to frequencies beyond the range of convenient measurement.

As an example of this method a series of readings is shown in full in the above table, the results being tabulated in a convenient manner for working out. For this series the values of P and Qf are plotted as above described, empirical formulæ are obtained for v_g'/v_g and $\tan \phi$, and a curve of amplification is plotted from this formula covering frequencies from 0·1 to 10 kilocycles. The phase angle is marked along the curve at intervals of 10°. Amplification curves are similarly plotted for a number of other transformers.

The greatest divergencies from the straight-line law are found in the case of the values of P for transformers having comparatively small inductance. In these cases the value of P is found to be less at low frequencies than would correspond to a straight-line plot. The reason for this would appear to be bound up with the variation of magnetic leakage due to varying flux density in the iron. As it was not readily possible to work at constant flux density this question was not followed up; it did not appear to be of practical importance as it did not occur to any material extent in the case of transformers having sufficient inductance.

The values of Qf showed satisfactory conformity with the above law in practically all cases.

It is clear from these results that both the real and imaginary terms in the denominator of v_g'/v_g vanish for a certain frequency. In the case of the Q term this frequency is well within the audible limit, and easily ascertainable by direct measurement. In the case of the P term, the vanishing frequency is considerably higher and, as a rule, outside the range of convenient measurement.

The frequency for which Q vanishes has been denoted as the "resonant frequency," because it is in practice very largely determined by the inductance and effective capacity of the transformer. Other factors have an influence on its value, notably the secondary resistance in a transformer having appreciable magnetic leakage, but even in this case the effect is precisely that of a virtual added capacity, so that the analogy to resonance is quantitative.

In the above,

$$\left.\begin{aligned} y &\equiv -\omega R^2 C \\ x &\equiv R' - R \end{aligned}\right\}\text{switch in position } (a)$$

or

$$\left.\begin{aligned} y &\equiv +\omega R^2 C \\ x &\equiv R' - R + \omega^2 R^3 C^2 \end{aligned}\right\}\text{switch in position } (b)$$

$$\text{Figures in last column} = \frac{1\,000 + R}{\sqrt{(x^2 + y^2)}}$$

TABLE 1.

Measurement of Amplification, Transformer No. 1.

f (kilocycles)	R	C	y	y^2	x	$Qf \times 10^3$	$P \times 10^3$	x^2	$x^2 + y^2$	Scalar amplification factor
0·40	1 044	0·0123	−30·8	950	44	−6·02	2·15	1 936	2 886	38·2
0·50	1 044	0·00758	−23·8	568	44	−5·82	2·15	1 936	2 504	40·9
0·75	1 033	0·00175	− 8·2	68	43	−3·03	2·10	1 849	1 917	46·8
1·00	1 033	0·0003	1·9	3·6	43	0·93	2·10	1 849	1 852	47·5
1·35	1 041	0·00085	7·2	52	41	4·74	2·01	1 681	1 733	49·0
1·70	1 039	0·00135	14·7	217	39·2	12·27	1·92	1 537	1 754	48·8
2·10	1 036	0·00165	21·7	472	36·5	22·5	1·79	1 332	1 804	48·0
2·50	1 032	0·00179	28·1	790	32·8	34·5	1·61	1 076	1 866	47·0
3·00	1 027	0·00195	36·8	1 355	28·3	54·5	1·40	801	2 156	43·6
3·60	1 018	0·00202	45·7	2 090	20·1	81·5	1·00	404	2 494	40·5
4·30	1 010	0·00210	54·3	2 945	12·9	116·0	0·65	166	3 111	36·0

The values of P and Qf are plotted in Fig. 7 *a*.

The frequency for which P vanishes (termed by Dye the "second resonance") marks in a general way the upper limit of effective amplification of a transformer, inasmuch as beyond this point both P and Q increase with the frequency, the former very steeply. The variation in the value of P has been shown in the foregoing to be due to the joint effects of magnetic leakage and self-capacity. In this connection the properties of iron at very low flux densities have to be borne in mind, the permeability of stalloy iron for the small alternating currents experienced under working conditions being of the order of 200–300. The consequence of this is that the coefficient of coupling between the two windings is very much less than would be the case if the flux density were of the value commonly experienced in power-transformer work.

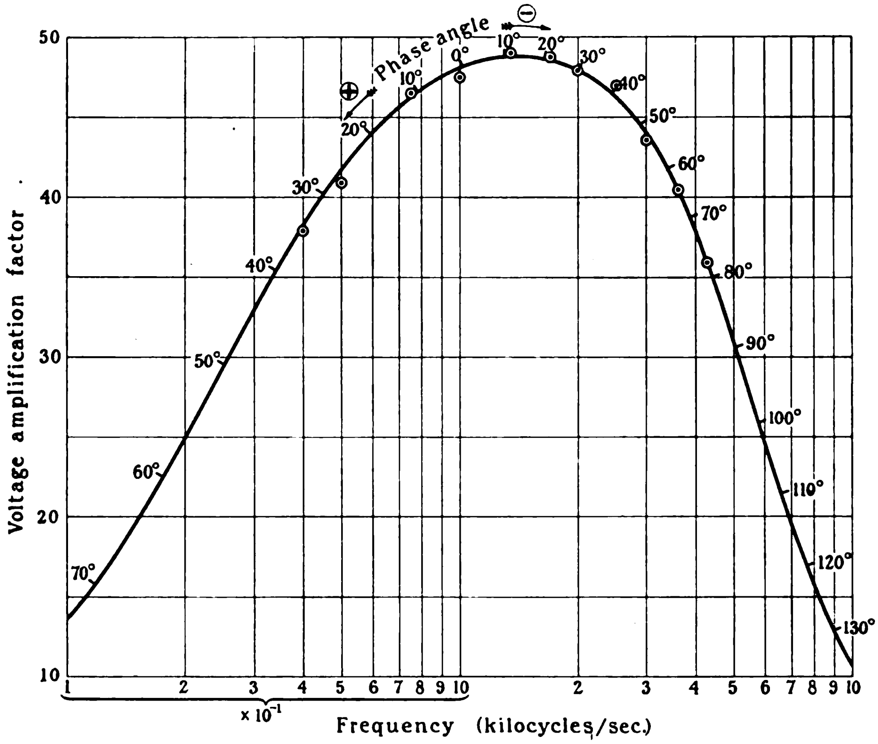


Fig. 7.—Transformer No. 1.

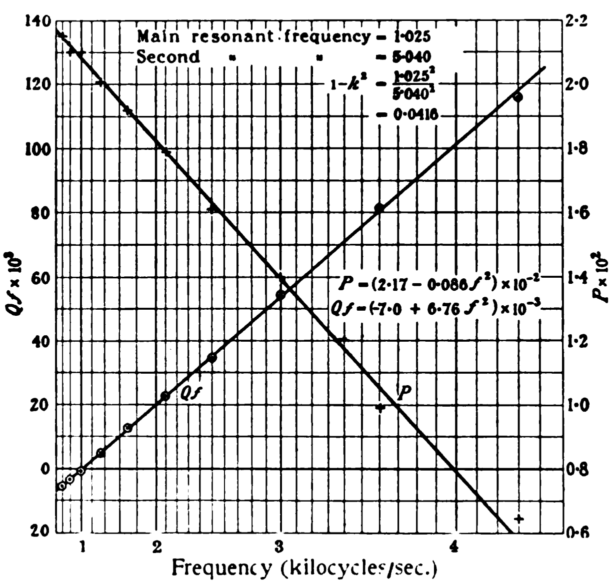


Fig. 7 *a*.—Transformer No. 1.

Between the two frequencies corresponding to $Q = 0$ and $P = 0$ respectively we invariably have a state of affairs in which P decreases while Q increases, and it is readily possible to design a transformer in which, over an appreciable band of frequencies, the one effect counteracts the other so far as the scalar response characteristic is concerned.

On the other hand, even with measurements extending up to 4 kilocycles only, the difference in performance between two such transformers can be readily estimated, inasmuch as in some cases the individual variations in P and Q are far less acute than in others. This is clearly shown in the series of curves to which reference has been made.

Description of Low-Leakage Transformer.

The transformer finally developed by the author and Mr. Ward was the result of an attempt to obtain the utmost constancy of P without the employment of a damping resistance. It is clear from the theory that in order to achieve this object we must reduce both l_2 and C_2 to the utmost possible extent and, whilst the importance of low self-capacity had been stressed in published work and in manufacturers' advertisements, the question of leakage inductance did not appear at

the date of the specification (Dec. 17, 1923) to have received the attention it deserved.

The reason for this seemed to be two-fold: first, that on the analogy of power transformers one would suppose that the leakage could be reduced well below 1 per cent simply by attention to the iron circuit, and, secondly, that in cases where it was clearly realized that a considerable percentage of leakage existed, it was actually considered a desirable characteristic inasmuch as it counteracted the effects of self-capacity.

The exacting requirements of faithful reproduction in broadcast reception indicated, however, that something further was required than merely the limited range of straight characteristic obtainable with a transformer constructed on normal lines, and the quality of reproduction in the upper register which was obtained as a result of the modified design appeared to justify this view.

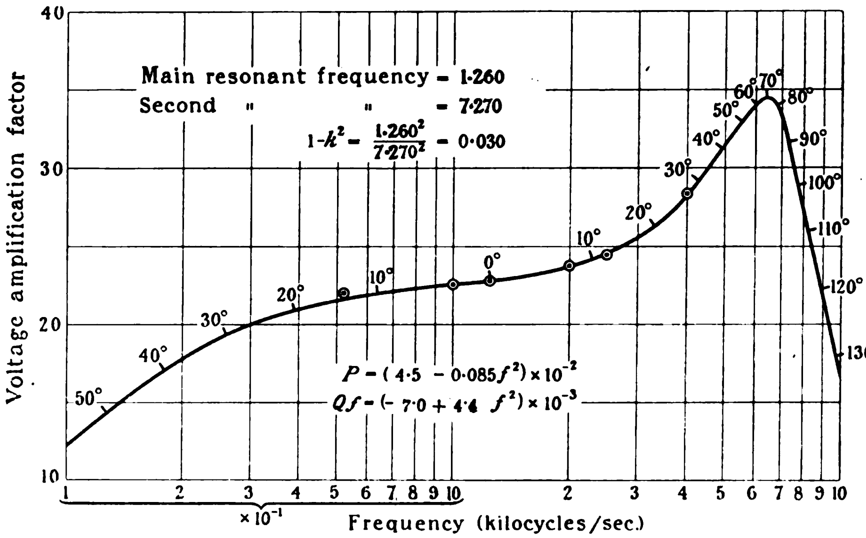


FIG. 8.—Transformer No. 2.

In order to reduce the value of leakage inductance the customary method was adopted of dividing the primary and secondary windings into sections and interleaving them. This was first attempted without any special precautions, but it was immediately found that the mutual capacity between primary and secondary gave a very heavy drop in the value of Y at high frequencies. Accordingly the sections were spaced apart from each other until no appreciable gain in respect of capacity was obtained by spacing them any further,

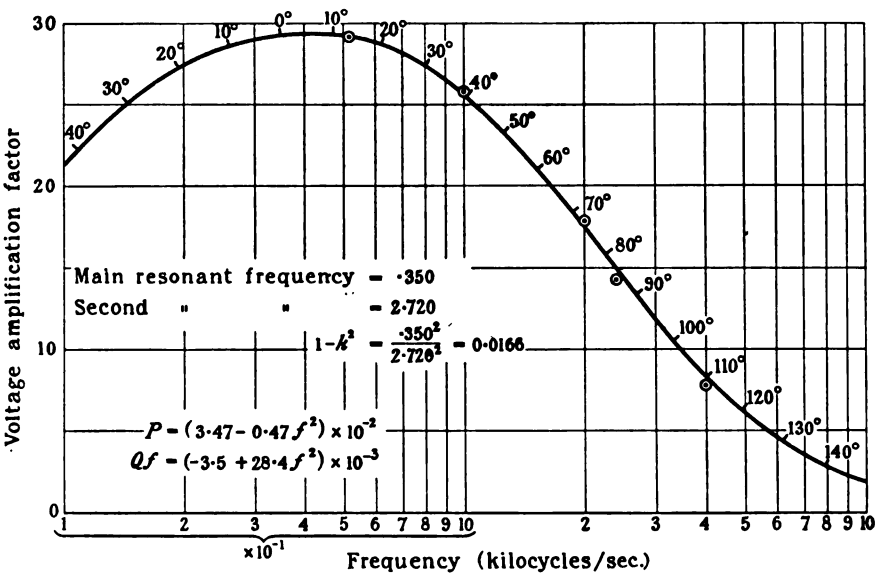


FIG. 9.—Transformer No. 3.

and the result was a transformer having the characteristics shown in Fig. 10.

A sectional view of the transformer is shown in Fig. 11, which is extracted from the patent specification. The sections C consisted in all cases of about 5 000 turns of 44 S.W.G. enamelled wire, but the gauge and number of turns of the sections B varied according to the ratio of the transformer.

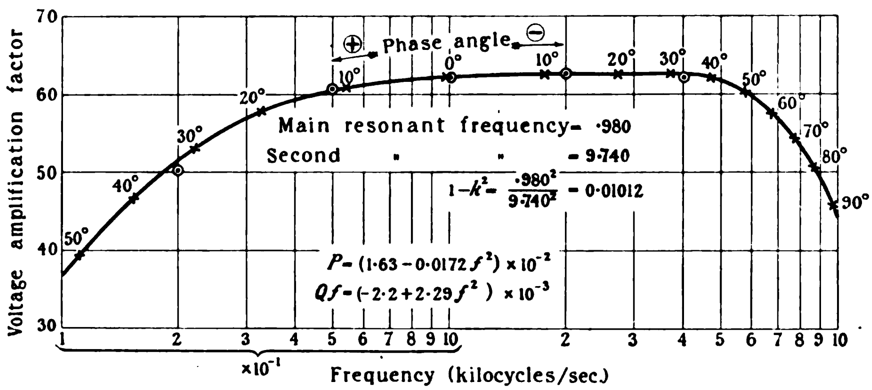


FIG. 10.—Transformer No. 4.

In order to space the sections apart from each other, star-shaped spacing-pieces of the kind shown in the figure (reference D) were used. These were made of strips of thin millboard situated edgewise on. Other methods have also been adopted to give an equivalent effect.

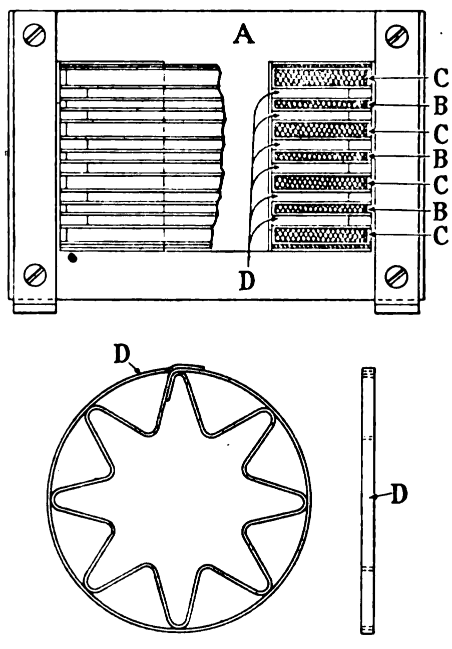


FIG. 11.

As will be seen from the figure, a shell-type iron core was employed consisting of T-shaped and U-shaped stalloy laminations lapped in the usual manner. These were secured by bolts passing through the corners, and it is worth noting in passing that there was no perceptible advantage of any kind to be obtained by not punching the laminations in this manner, nor did it appear to make any difference whether the bolts were insulated or not.

The cross-section of the iron core was about 5·5 cm² and the length of the iron circuit 18 cm. The average effective shunt resistance across the secondary winding has been worked out from a set of circle diagrams of primary impedance furnished to the author by Mr. E. C. Cork; its value was approximately 8 megohms, though it varied somewhat with different transformers. In view of the fact that it was necessary that the resistance thrown into the secondary winding from the anode circuit of the valve should have a value of the order of 0·25 megohm it will readily be seen that no very great gain was to be expected by improving the transformer in respect of losses, and this would appear to account for the point mentioned above regarding the bolting of the laminations.

The secondary inductance of these transformers was of the order of 300–350 H and the effective leakage was about 1 per cent. The latter varied slightly with different ratios of transformer, an improvement being found in the case of the lower ratios where the density of primary winding was greater. The variation was probably due to the different gauges of wire used and the different manner in which the winding space was filled up.

Four different ratios of transformer were specified. The lowest of 2·7 : 1 was suitable for use in conjunction with valves having an impedance of about 40 000 ohms, such as the ordinary R type. The transformer of ratio 4 : 1 operated very satisfactorily in conjunction with a valve of about 16 000 to 18 000 ohms impedance; the 6 : 1 ratio with a 7 000-ohm valve, and the 8 : 1 with a valve of 4 000 to 5 000 ohms impedance. This last transformer is also useful after a crystal rectifier, though it is doubtful whether it has a sufficiently high step-up ratio for some of the very low-resistance crystals.

All of the above transformers appear in general use to offer one very definite advantage, namely a comparative immunity from reaction effects tending to self-oscillation or distortion. It has been the belief of the author for some time that a transformer of low leakage

inductance is inherently more stable in cascade amplification, and measurements on the effect of the impedance of the windings of one transformer on the amplification of another, due to the grid-filament capacity of the valves appeared to support this contention.

There appears also to be some justification for the view that actually better reproduction is given with a low-leakage transformer amplifier on the frequencies, say, up to 5 000 cycles than with transformers of the ordinary type which are carefully adjusted to give a uniform amplification curve up to this frequency and no further. At any rate it appears desirable, for really good-quality reproduction, to place the second resonance of the transformer at the very highest possible frequency, and a value of 8 000 to 10 000 cycles does not appear by any means to be excessive. The transformer shown in Fig. 10 has a second resonance of 9 740 cycles.

The defect of the transformer characteristic under consideration is undoubtedly the inefficient reproduction of the lower frequencies, and it is of interest to note that, in a transformer embodying the same principles of design which has been recently developed and put on the market, this deficiency has been made good with very little sacrifice on the upper register.

Notes on Transformer Characteristics.

In order to carry out a practical analysis of a transformer we can make use of the vector response-characteristics plotted in the manner already described, and this method has the advantage that we obtain the constants of the transformer under actual working conditions.

An approximate method, which is quite satisfactory in nearly all cases, is to neglect the transformer resistance. We then take the main and second resonant frequencies given by equating Q and P respectively to zero. Denoting these by ω_0 and ω_0' (in radians per sec.) we have

$$L_1C_1\omega_0^2 = 1$$

and

$$(1 - k^2)L_1C_1(\omega_0')^2 = 1$$

Hence

$$1 - k^2 = \frac{(\omega_0')^2}{\omega_0^2} = \frac{(f_0')^2}{f_0^2}$$

(f_0' and f_0 being the corresponding frequencies).

To find L_1 and C_1 separately we require to know the valve resistance r_a.

Since $-\frac{v_g'}{v_g} = \frac{1}{P + jQ}$ we have by comparison with equation (6)

$$-\frac{P}{Qf} = \frac{(1 - \omega^2 l_2 C_2)}{(r_a\sigma^2/6\,280L_2) + \text{terms containing } \omega} = \frac{(1 - \omega^2 l_2 C_2)6\,280L_1}{r_a + \ldots \text{etc.}}$$

If we equate f to zero we thus have

$$\left(-\frac{P}{Qf}\right)_{f=0} = \frac{6\,280L_1}{r_a}$$

Hence

$$L_1 = \frac{r_a}{6\,280}\left(-\frac{P}{Qf}\right)_{f=0}$$

Taking the transformer shown in Fig. 10, it was found that $r_a = 19\,100$ ohms.

Hence $$L_1 = \frac{19\,100}{6\,280} \times \frac{1\cdot 63}{2\cdot 20} = 22\cdot 6 \text{ H}$$

On measurement the value of L_1 was found to be 21·6 H, and the resonant resistance of the primary came out to 0·6 megohm.

In order to obtain a more accurate estimate of L_1 from the curve, we may employ the figure of 0·6 megohm to apply a correction. We have, by comparison with equation (1) instead of (6) :—

$$-\frac{P}{Qf} = \frac{\left(1 + \frac{r_a\sigma^2}{r^2} - \omega^2 l_2 C_2\right)6\,280L_1}{r_a + \text{terms containing } \omega}$$

Hence $$\left(-\frac{P}{Qf}\right)_{f=0} = \frac{[1 + (r_a/r_1)]6\,280L_1}{r_a}$$

and thus $$L_1 = \frac{r_a}{6\,280[1 + (r_a/_1r)]} \times \left(-\frac{P}{Qf}\right)_{f=0}$$

The corrected value of L_1 is thus reduced in the ratio

$$\frac{1}{1 + (19\cdot 1/600)} = \frac{1}{1\cdot 031}$$

i.e. instead of 22·6 H we have a figure of 21·9 H, which is in good agreement with the measured value.

Referring to Fig. 10 it will be seen that $1 - k^2 = 0\cdot 0101$. Taking this as an approximate value we can calculate C_1, taking the values of l_1 and r_1 correctly into account. It will readily be seen from equation (1) that at the frequency for which $Q = 0$ we have

$$L_1\left(C_1 + \frac{l_1}{r_1 r_a}\right)\omega^2 = 1$$

Hence

$$C_1 + \frac{0\cdot 22}{0\cdot 6 \times 0\cdot 019} \times 10^{-12} = \frac{10^{-6}}{21\cdot 9 \times 6\cdot 28 \times 0\cdot 980}$$

i.e.

$$\begin{aligned} C_1 &= 0\cdot 00121 - 0\cdot 000019 \\ &= 0\cdot 00119\ \mu\text{F} \end{aligned}$$

Hence the virtual capacity due to leakage and losses is only of the order of 2 per cent of the actual capacity, and, in consequence, there is no material error in the calculation of $1 - k^2$.

The values of L_2 and C_2 can be obtained from the known value of σ and work out to 350 H and 0·000074 μF. The latter includes the capacity of the valve to which the transformer is connected. The value of l_2 is of course 3·5 H.

The method of measuring m and r_a for the above purposes may be of interest. To obtain m, two high-quality choke coils of very low resistance were constructed having an inductance of the order of 100 H and a resonant impedance of the order of 20 megohms or more. These were arranged as an intervalve coupling unit and connected to the bridge in the same manner as an intervalve transformer (cf. Fig. 12).

The amplification of the stage was thus equal to the value of m for the valve, and the conditions under which any transformer was tested could thus be immediately reproduced.

In view of the high impedance of the chokes no correction was necessary in practice, and it may further

be noted that it is not essential actually to make the measurement at the resonant frequency of the chokes since, provided the coupling condenser is large enough, the amplification factor is simply $1/P$.

In order to measure r_a an arrangement similar to that shown in Fig. 13 was employed. Here it will be noted that the high-tension supply is fed to the valve through a choke (which in the actual experiments was one of those used for the previous test) and the anode resistance

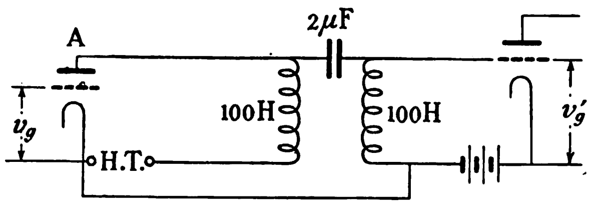


Fig. 12.—Measurement of m.

$-v_g'/v_g$ = magnification factor of valve A.

is coupled by a condenser so as to be in effect a shunt across one of the 1 000-ohm arms of the bridge. Assuming this to be the arm adjacent to R_1 we have at once

$$\frac{1}{R_1} = \frac{1}{1\ 000} + \frac{1}{r_a}$$

from which r_a can be calculated.

The impedance of the coupling condenser makes it necessary to employ a capacity across one of the other ratio arms in order to balance the bridge, but the error as far as the measurement of resistance is concerned

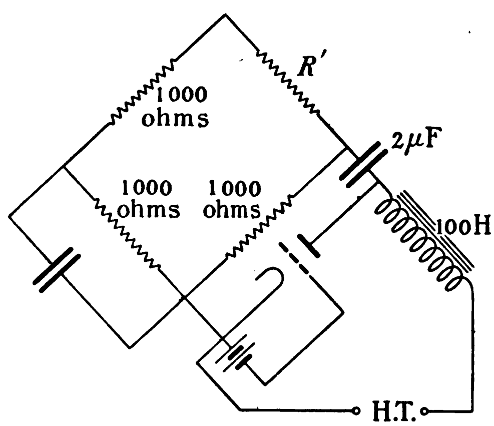


Fig. 13.—Measurement of r_a.

can easily be made insignificant by choosing a large enough condenser and working on a high enough frequency. A capacity of 2 μF at a frequency of 1 000 cycles is good enough for all practical values of r_a.

The Choice of a Valve.

No consideration has so far been given to the question of a valve for use in conjunction with an intervalve transformer, and it is of importance to review certain factors in this connection.

Referring to the simplest case as exemplified in equation (8), it is evident that the shape of the response characteristic is determined by the product $r_a\sigma^2$, whereas the peak value is determined by $m\sigma$.

Suppose that we consider a series of valves and transformers for which $r_a\sigma^2$ is constant, and endeavour to work out the peak value of amplification from them.

Then we may write $\quad r_a\sigma^2 = K$

and thus $\quad \sigma = \sqrt{\frac{K}{r_a}}$

Hence the peak amplification is equal to $m\sqrt{(K/r_a)}$ and is thus proportional to $m/\sqrt{r_a}$.

Now if we take a range of valves in which the electrodes occupy the same geometrical positions and the emissions are the same but the density of the grid windings are different, we find in practice that the value of m/r_a is approximately constant.

It is thus evident that the peak amplification is proportional to the square root of the amplification factor of the valve. As evidence of this effect it is worth while to compare the curves in Figs. 7 and 10. In the former case the valve had an impedance of 7 000 ohms and a magnification factor of 5·5. In the latter case the corresponding values were 19 100 ohms and a magnification of 15·6. The ratios are thus substantially the same, but even with the very steep curve shown on the transformer in Fig. 7 it fails to attain the maximum amplification of the transformer in Fig. 10. Had the characteristic in the former case been of a 6 : 1 transformer of the same type as that shown in Fig. 10, the characteristic would have been of substantially the same shape and the maximum amplification about 33 (these figures are taken from published characteristics of the transformer in question).

It thus appears that a very considerable gain is to be expected from the employment of a valve of high magnification factor and a transformer of conservative step-up ratio, and there seems to be little doubt that, if a valve could be produced having an impedance of the order of 0·25 megohm and a proportionate amplification factor, the best form of intervalve coupling would be of the choke type. This, however, neglects practical difficulties such as questions of battery supply, which must of necessity enter into any consideration of this kind.

As an offset to the advantages gained by the employment of a valve of high magnification factor it is further worth while remarking that it is a matter of great difficulty to produce such a valve with a sufficiently straight characteristic to avoid asymmetric distortion on the high and low frequencies respectively. The use of such valves is thus of greater advantage in the earlier stages of an amplifier where the voltage amplitude is small.

A further question must also be considered, namely, the greater effect of inter-electrode capacity in a valve of this kind, since the capacity is at least as great if not greater than with open-mesh valves, and the voltage developed across this capacity is of course considerably greater.

The Effect of Inter-electrode Capacity.

No attempt can be made to deal thoroughly in this paper with this very intricate question, but a few general considerations may be briefly outlined.

It is well known that the effect of an impedance in the anode circuit of a valve on a preceding stage of amplification can be represented by an input impedance across the grid and filament, and it is possible to calculate this on the basis of the theory previously given.

Referring to Fig. 14, C_0 is the anode-grid capacity of a thermionic valve and i_0 the current flowing through it in response to an E.M.F. v_g across the grid and filament. Z_a is the impedance in the anode circuit and Z_g the effective input impedance due to C_0.

Then $$i_0 = j\omega C_0(v_g - v_a)$$

Now $$\frac{v_a}{v_g} = -\frac{m}{1 + (r_a/Z_a)}$$

Hence $$i_0 = j\omega C_0 v_g\left[1 + \frac{m}{1 + (r_a/Z_a)}\right]$$

and we have

$$\frac{1}{Z_g} = j\omega C_0\left[1 + \frac{m}{1 + r_a(/Z_a)}\right]$$

The input impedance thus consists of two parallel

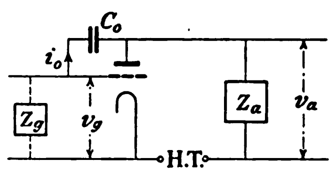


FIG. 14.

branches, a capacity equal to C_0 and an impedance equal to

$$\frac{1 + (r_a/Z_a)}{j\omega m C_0}$$

We need only concern ourselves with the latter, since the former can be counted as a part of the transformer capacity.

If we neglect the resistance of the transformer we may write

$$\frac{1}{Z_a} = \frac{1}{j\omega L_1} + \frac{1}{j\omega l_1 + (1/j\omega C_1)}$$

in accordance with the simplifications of Fig. 2.

We shall then obtain the result

$$Z_g = \frac{1}{j\omega m C_0} - \frac{r_a}{mL_1 C_0 \omega^2} + \frac{r_a C_1/(mC_0)}{1 - l_1 C_1 \omega^2}$$

It thus appears that the input impedance can be represented by a condenser of value mC_0 in series with a resistance the value of which varies with the frequency and may be either positive or negative.

The feature of interest in this connection is the effect of leakage inductance. If we write $l_1 = 0$, the equation reduces to

$$Z_g = \frac{1}{j\omega m C_0} - \frac{r_a}{mL_1 C_0 \omega^2}(1 - L_1 C_1 \omega^2)$$

Hence the resistance has zero value at the resonant frequency of the transformer, is negative below this frequency and positive above it, remaining positive however high the frequency is raised.

Now for values of ω below the main resonant frequency of a transformer the effect of the negative resistance is not enough to cause any serious disturbance of the resonance curve of a preceding stage, inasmuch as the reactance of the effective capacity mC_0 is so high. This can easily be verified by actual measurements. Hence, in the absence of magnetic leakage, the only effect of any consequence is at high frequencies and manifests itself as a capacity in series with a positive resistance across the secondary of the transformer.

If we consider the case where l_1 is finite it is at once apparent that if $l_1 C_1 \omega^2 > 1$ the resistance is again negative. Hence we may expect a regenerative effect

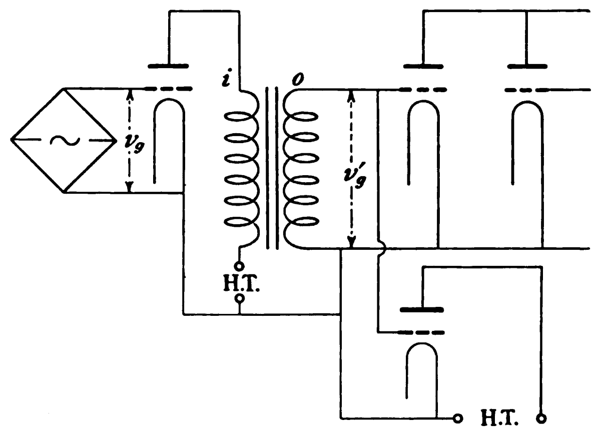


FIG. 15.

above the second resonance, and this will be far more serious owing to the lessened reactance of mC_0. This appears to be the cause of whistling and distortion on the upper frequencies, which are so often encountered in the case of transformers having the second resonant frequency not high enough. Transformers which have a high second resonance will occasionally go into oscillation on an inaudibly high frequency, but this is not generally difficult to suppress without impairing the amplification characteristic over the important frequency range.

Within the normal audio-frequency range the input load takes the form of an addition to the self-capacity of the transformer. This can usually be allowed for by a slightly conservative step-up ratio. On the other hand, with a transformer of low leakage inductance the use of the neutrodyne circuit becomes practicable.*

In order to form an estimate of the possibilities in this direction, and also to investigate the nature of the reaction effect in a stage of audio-frequency amplification, a series of tests was carried out with the circuit arrangements shown in Figs. 15, 16, 17 and 18, the results being given in Tables 2 to 5.

Referring to Fig. 15, it will be seen that the valve is inserted with its grid and filament shunted across a transformer in a normal manner for bridge measurement, but with its windings in opposite senses. The arrangement with Fig. 15 shows no impedance in the anode circuit of its additional valve, so that only the normal capacities between grid and filament and grid and plate are added to the secondary capacity of the transformer.

* Cf. *Proceedings of the Institute of Radio Engineers*, 1926, vol. 14, p. 231.

In Fig. 16 the same arrangement is employed except that a transformer is connected in the anode circuit of the additional valve, this being the same transformer as was used for the plotting of the characteristic shown in Fig. 8.

In Fig. 17 a small neutralizing condenser is connected on the plate of the additional valve to the plate of the amplifying valve; otherwise the arrangement is as in Fig. 16.

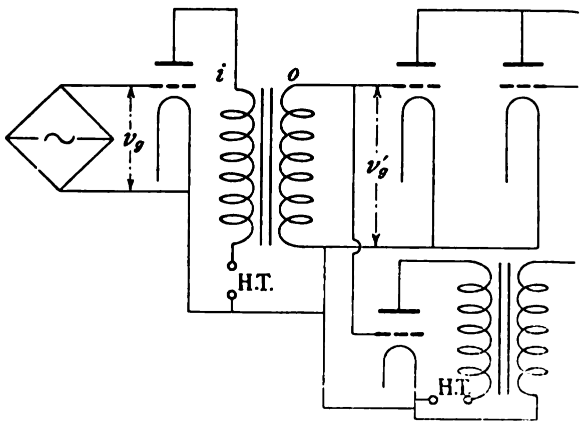


Fig. 16.

In Fig. 18 a 0·0003 μF condenser is shunted across the secondary of the transformer connected to the additional valve. This has the effect of lowering the second resonance very considerably and bringing it within the range of practical measurement, in fact to about 2·7 kilocycles.

The measurements with these various arrangements are given in Tables 2 to 5. Table 2 shows that the

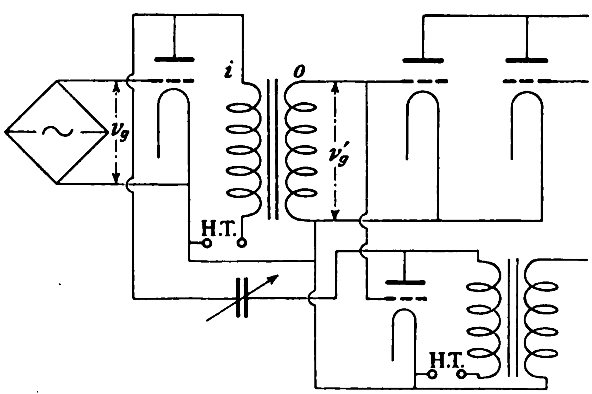


Fig. 17.

amplification characteristic of the transformer is quite normal, the curve being that corresponding approximately to the characteristic shown in Fig. 10 but measured on a different occasion.

Table 3 shows a small change in the value of P_2 as a result of reaction from the second stage, but a very steep rise in the value of Q_2. This is what would be expected, since within the range of frequencies measured the reactance of the transformer primary is capacitative and very high.

In Table 4 it will be seen that the values of Q_3 are substantially the same as those of Q_1. This was deliberately arranged by a suitable adjustment of the neutralizing condenser. Under these conditions the

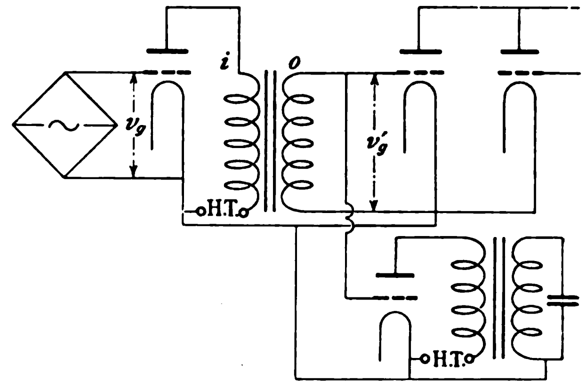


Fig. 18.

values of P_3 drop more steeply than those of P_1 and a rising characteristic is obtained. If, however, the neutralizing condenser had been so adjusted as to permit

Table 2.

Effect of Inter-electrode Capacity.

Second stage inoperative (see Fig. 15).

f (kilocycles)	$P_1 \times 10^2$	$Q_1 \times 10^2$	$\frac{1}{\sqrt{(P_1^2 + Q_1^2)}}$
1·00	1·63	0·07	61·3
1·50	1·59	0·25	62·1
2·00	1·55	0·42	62·1
3·00	1·42	0·71	63·1
4·00	1·24	0·98	63·1

Table 3.

Effect of Inter-electrode Capacity.

Second stage operative; second transformer unloaded (see Fig. 16).

f (kilocycles)	$P_2 \times 10^2$	$Q_2 \times 10^2$	$\frac{1}{\sqrt{(P_2^2 + Q_2^2)}}$
1·00	1·57	0·42	61·5
1·50	1·52	0·84	57·6
2·00	1·46	1·12	54·4
3·00	1·28	1·75	46·1
4·00	1·03	2·32	38·3

of a small additional increase in the value of P_3, a flat characteristic could have been obtained but the extent would not have been as great as that of a transformer operating under the conditions of normal measurement.

The imperfect neutralization is due to the magnetic leakage of the first transformer.

In Table 5 we see the effect of reaction from a subsequent stage both below and above the second resonant frequency, the first three figures for P_4 being definitely greater than the corresponding figures in Table 2, showing the positive resistance thrown into the amplifying circuit, and the last two figures being less, in the second case very considerably so. As far as the values of Q_4 are concerned these are always increased, as would be expected, but the increase is a minimum in the neighbourhood of the second resonance, viz. at 3·00 kilocycles.

TABLE 4.

Effect of Inter-electrode Capacity.

Second stage operative but neutralized; second transformer unloaded (see Fig. 17).

f (kilocycles)	$P_3 \times 10^2$	$Q_3 \times 10^2$	$\dfrac{1}{\sqrt{(P_3^2 + Q_3^2)}}$
1·00	1·60	0·07	62·5
1·50	1·53	0·25	64·5
2·00	1·43	0·42	67·0
3·00	1·14	0·71	74·5
4·00	0·76	1·02	79·5

The most interesting feature of these measurements appears to be the successful manner in which audio-frequency neutralization can be carried out, and it would seem that this aspect of the problem of designing audio-frequency transformer amplifiers has been undeservedly neglected.

TABLE 5.

Effect of Inter-electrode Capacity.

Second stage operative; second transformer loaded (see Fig. 18).

f (kilocycles)	$P_4 \times 10^2$	$Q_4 \times 10^2$	$\dfrac{1}{\sqrt{(P_4^2 + Q_4^2)}}$
1·00	1·71	0·40	56·9
1·50	1·78	0·56	53·6
2·00	1·78	0·75	51·8
3·00	1·39	0·87	61·0
4·00	0·65	1·24	71·5

VARIOUS INTERVALVE TRANSFORMER CONNECTIONS.

(*a*) *Primary series-condenser circuit.*—If a condenser of suitable value is placed in series with the primary winding of a low-frequency transformer, an increase of amplification may be obtained at frequencies below the main resonance of the transformer, the effect being exactly analogous to that of magnetic leakage at high frequencies. Circuits embodying this principle have been published by various workers.

In order to carry out this scheme, it is necessary to provide means for feeding the anode of the associated valve with high-tension voltage, and this can best be effected by means of a parallel choke arrangement as shown in Fig. 19.

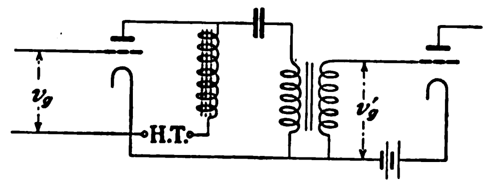


FIG. 19.

For the sake of simplicity we may neglect magnetic leakage and resistance in the transformer, and the figure may be redrawn, on the analogy of Fig. 2, as shown in Fig. 20.

With the notation of this figure we can readily obtain the result

$$-\frac{v'_g}{v_g} = \frac{m\sigma}{1 - \dfrac{1}{L_1 C\omega^2} + jr_a\left(C_1\omega - \dfrac{1}{L_1\omega}\right)}$$

(C_1/C being neglected in comparison with unity, which is legitimate under practical conditions).

The scalar amplification factor is given by

$$\frac{V'_g}{V_g} = \frac{m\sigma}{\sqrt{\left[1 + r_a{}^2\dfrac{C_1}{L_1} + \left(\dfrac{r_a{}^2}{L_1^2} - \dfrac{2}{L_1 C}\right)\dfrac{1}{\omega^2} + \dfrac{1}{L_1^2 C^2\omega^4} + r_a{}^2 C_1^2\omega^2\right]}}$$

Now at low frequencies $r_a{}^2 C_1^2\omega^2$ can be neglected in comparison with unity. If at such frequencies $1/(L_1^2 C^2\omega^4)$ can also be neglected, the constancy of amplification is governed by the coefficient of $1/\omega^2$, and the characteristic rises or falls according as $2L_1/C >$ or $< r_a{}^2$, a flat characteristic being given by $2L_1/C = r_a$.

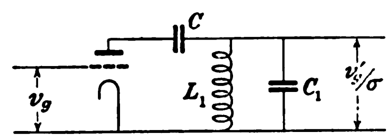


FIG. 20.

At very low frequencies the term $1/(L_1^2 C^2\omega^4)$ begins to have weight, and below a certain frequency the amplification is reduced by the presence of the series condenser.

The disadvantage of this arrangement would appear to be an increased tendency towards asymmetric distortion at low frequencies. There is no doubt that the inductance of the windings of an intervalve transformer carrying no polarizing current increases with increasing flux density, but, however much it increases, the magnification cannot exceed the value $m\sigma$ when it is normally connected. With the series-condenser arrangement there is a possibility of a large resonance

hump at high amplitudes, since in this case $2L_1/C$ may be greater than r_a^2.

As an illustration of this method, a resonance curve was taken for transformer No. 4, with a condenser of 0·07 μF capacity in series with the primary and a feed-choke of 100 H. The results are given in Table 6, P_1 and Q_1 being the values of P and Q with the condenser short-circuited, and P_2 and Q_2 with the condenser in circuit.

TABLE 6.

f (kilocycles)	$P_1\times 10^2$	$Q_1\times 10^2$	$\left(\frac{V_g'}{V_g}\right)_1$	$P_2\times 10^2$	$Q_2\times 10^2$	$\left(\frac{V_g'}{V_g}\right)_2$
0·20	1·64	1·28	48·1	1·02	1·22	62·9
0·30	1·64	0·81	54·6	1·37	0·81	62·9
0·40	1·63	0·62	57·5	1·50	0·57	62·5
0·50	1·63	0·41	59·5	1·60	0·41	60·5
1·00	1·62	—	61·7	1·62	—	61·7

It will be noted that with the condenser in circuit a progressive decrease of P_2 is obtained with decreasing frequency which off-sets with a good measure of accuracy the increase of Q_2, giving uniform amplification.

(b) *Low-frequency reaction circuits.*—It is possible to compensate for the loss of amplification in an intervalve transformer circuit at both high and low frequencies by means of reaction. In order to consider the possibilities in this direction, it is convenient to take the case of low frequencies and to compare the effect obtained with that given by the condenser circuit above described.

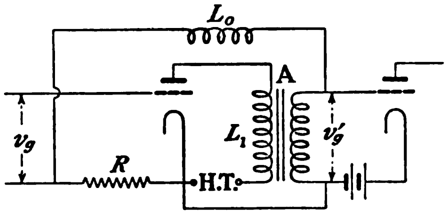


FIG. 21.

Referring to Fig. 21, A is a transformer the windings of which are oppositely connected so that σ is negative. The grid terminal of the secondary is connected through an inductance L_0 to a resistance R which is situated in the grid circuit of the input valve. The impedance of L_0 is arranged to be large in comparison with R at practical low audio frequencies.

Under these conditions we have two effects to consider :—(a) the loss of primary inductance due to L_0 being shunted across the secondary of the transformer, and (b) the effect of the reaction potential developed across R.

Considering (a), if L_1' be the effective primary inductance and L_1 its normal value, we have

$$\frac{1}{L_1'} = \frac{1}{L} + \frac{\sigma^2}{L_0} \text{ (} R \text{ being neglected)}$$

Now if the potential across R be denoted by v_r we have

$$\frac{v_g'}{v_g + v_r} = \frac{m\sigma}{1 + (r_a/Z)} \text{ (where } Z = \text{anode impedance)}$$

$$= \frac{m\sigma}{1 + \frac{r_a}{j\omega}\left(\frac{1}{L_1} + \frac{\sigma^2}{L_0}\right)} \text{ (at low frequencies)}$$

and $$v_r = \frac{R}{j\omega L_0} v_g', \text{ since } \omega L_0 >> R$$

Hence

$$v_g'\left[1 + \frac{r_a}{j\omega}\left(\frac{1}{L_1} + \frac{\sigma^2}{L_0}\right)\right] = m\sigma v_g + \frac{m\sigma R}{j\omega L_0} v_g'$$

If then we make

$$\frac{m\sigma R}{L_0} = r_a\left(\frac{1}{L_1} + \frac{\sigma^2}{L_0}\right)$$

we have

$$\frac{v_g'}{v_g} = m\sigma \text{ at low frequencies,}$$

i.e. constancy of amplification is attained.

A more detailed consideration of this case shows that the amplification at high frequencies is substantially unaltered by the inductance L_0, the only effect being as if the inductance of the transformer were made infinite within the limits of effective operation of the reaction circuit.

The contrast between the method of working and that considered under heading (a) is noteworthy. In the latter case the increase in Q is compensated by a drop in P; according to the present method this increase is itself annulled.

In practice this circuit is quite readily workable, L_0 being a fixed inductance and R a variable resistance of the graphite-leak type. It is found that if R be increased, a setting is reached where oscillations occur on a very low frequency. On setting R to a value close to but definitely below this point, a stable arrangement is obtained and a great increase results in the low-frequency amplification.

The effective limit of this circuit is found when the value of R starts to be comparable with the impedance of L_0. The immediate effect is a drop in the value of P, which gives a still further increase in amplification and is apparently the cause of self-oscillation when R is increased, a frequency being found where $P = 0$ and $Q = 0$ simultaneously. The effect at very low frequencies must necessarily be a decrease in amplification as in the case considered under (a), but a very much greater range of constant amplification may be attained by the present method.

Table 7 gives the results of a series of measurements on a small transformer with and without the correcting device. As before, P_1 and Q_1 correspond to the normal circuit arrangement and P_2 and Q_2 to the circuit shown in Fig. 21.

The asymmetric distortion in an arrangement of this sort would appear to be definitely diminished as far as the iron is concerned, though undoubtedly there is a

danger of introducing valve distortion in its place. How far this latter effect would be troublesome is a matter for further experiment.

Other low-frequency reaction effects may be obtained by shunting L_0 with a small condenser (which annuls the increase in Q at high frequencies) or a high resistance (which increases the amplification at middle frequencies). The condenser circuit has the disadvantage that high-frequency oscillations are very readily set up owing to magnetic leakage, and also that inter-electrode capacity couplings appear to upset the circuit when it is used as part of an amplifier, even though it

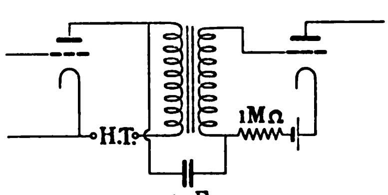


FIG. 22.

operates in accordance with theory when connected to the bridge. The resistance connection produces a very great increase of amplification at some sacrifice of quality.

(c) *Auto-transformer circuit.*—An arrangement due to Messrs. Graham and Rickets is illustrated in Fig. 22 and is well worth consideration.

Here the transformer is connected so that σ is positive, and the plate end of the primary winding is coupled through a condenser to the filament end of the secondary, the latter being connected to the grid battery through a high resistance. The values of 1 μF and 1 megohm were arbitrarily chosen but appeared to give satisfactory results.

It is obvious from the circuit that the effect of the arrangement is roughly to increase σ to $(\sigma + 1)$. This is achieved at the expense of some slight increase in the self-capacity of the transformer, due apparently to the increased mean alternating potential between the windings. The figures are given in Table 8.

TABLE 7.

f (kilocycles)	$P_1 \times 10^2$	$Q_1 \times 10^2$	$\left(\frac{V'_g}{V_g}\right)_1$	$P_2 \times 10^2$	$Q_2 \times 10^2$	$\left(\frac{V'_g}{V_g}\right)_2$
0·20	1·96	− 2·69	30	1·80	− 0·35	54·5
0·33	1·97	− 1·86	36·8	1·86	− 0·22	53·4
0·50	1·98	− 1·04	44·6	1·92	− 0·11	51·9
0·67	1·98	− 0·77	47·0	1·92	− 0·07	51·9
1·00	1·95	− 0·45	49·8	1·92	0	52·0
2·00	1·92	0·05	51·8	1·88	0·05	58·1
4·00	1·78	0·23	55·5	1·72	0·22	57·7

TABLE 8.

f (cycles)	$P_1 \times 10^2$	$Q_1 \times 10^2$	$\left(\frac{V'_g}{V_g}\right)_1$	$P_2 \times 10^2$	$Q_2 \times 10^2$	$\left(\frac{V'_g}{V_g}\right)_2$
0·33	1·59	− 0·55	59·1	1·30	− 0·39	73·6
0·50	1·60	− 0·39	60·6	1·30	− 3·26	75·7
0·67	1·60	− 0·24	61·7	1·28	− 0·11	77·8
1·00	1·59	0	62·7	1·27	0·05	78·7
2·00	1·54	0·23	64·2	1·24	0·34	77·7
3·00	1·45	0·44	66	1·18	0·60	75·8
4·00	1·33	0·65	67·1	1·08	0·84	73

CONCLUSION.

The author would like to express his thanks to Mr. E. C. Cork for the information referred to on page 1074, to Mr. L. E. Currah, Associate Member, for reading the proofs of the paper, and to Messrs. A. J. Franklin and A. D. Hodgson for assistance in taking some of the measurements.

APPENDIX.

(A) THE EFFECT OF PRIMARY CAPACITY.

If a condenser is connected across the primary winding of a transformer a modification is required to the previous equations, which become slightly more complex. This case is of interest, both on account of the use of condensers in this manner to by-pass high-frequency currents and as representing a certain tendency in

transformer design, the only object of which is to improve the response characteristic.

Supposing that in Fig. 2 there is a condenser C_1' across L_1, we may evaluate v_g'/v_g by substituting $1/L - \omega^2 C_1'$ for $1/L_1$. This gives

$$\frac{v_g'}{v_g} = \frac{m\sigma}{1-\omega^2 l_1 C_1 + jr_a\left[\omega\left(C_1 + C_1' + \frac{l_1}{r_1 r_a}\right) - \frac{1}{\omega L} - \omega^3 l_1 C_1 C_1'\right]}$$

l_1/L_1 being neglected in comparison with unity.

If we neglect transformer losses, we may express the condition for a flat characteristic as in the case of equation (7), only in this case we have another disposable constant, i.e. C_1', and can thus make the coefficient of ω^4 zero as well as that of ω^2. We have

$$\sqrt{(X^2+Y^2)} = \sqrt{\left[1 - 2\omega^2 l_1 C_1 + \omega^4 l_1^2 C_1^2 - 2r_a^2\frac{(C_1 + C_1')}{L_1} + \omega^2 r_a^2 (C_1 + C_1')^2 - 2\omega^4 r_a^2 l_1 C_1 C_1'(C_1 + C_1') + 2\omega^2 r_a^2 \frac{l_1}{L_1} C_1 C_1' + \frac{r_a^2}{\omega^2 L_1^2} + \omega^6 r_a^2 l_1^2 C_1^2 C_1'^2\right]}$$

For the optimum characteristic we have therefore

$$2l_1 C_1 = r_a^2 (C_1 + C_1')^2 + 2r_a^2 \frac{l_1}{L_1} C_1 C_1'$$
$$l_1^2 C_1^2 = 2r_a^2 l_1 C_1 C_1'(C_1 + C_1')$$

Neglecting l_1/L_1 in comparison with unity (i.e. omitting the second term on the right-hand side of the first equation), this reduces to

$$C_1' = \frac{1}{3}C_1 \quad \text{and} \quad \frac{l_1}{C_1} = \frac{8}{9}r_a^2$$

If these conditions are satisfied we shall have only the term containing ω^6 remaining in the denominator, and thus a greater extent of straight characteristic is obtainable. On the other hand, it is necessary for C_1 to be less, i.e. a smaller step-up ratio must be employed, with a consequent sacrifice in amplification.

The analogy of this system to a low-pass filter is interesting. What we have in effect at the high frequencies is shown in Fig. 23. And we find that v_g'/v_g can be reduced to an expression of the form $m\sigma/\sqrt{(A + B\omega^6)}$ by satisfying two equations among the four quantities l_1, C_1, C_1' and r_a. Assuming r_a to be given, we can satisfy one more equation which will determine the frequency for which the "cut-off" becomes effective.

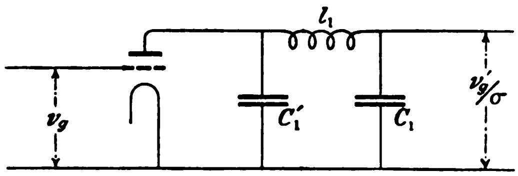


FIG. 23.

If we add a further inductance and condenser as in Fig. 24, we now have two more disposable constants with which we can satisfy two more equations (i.e. equating the coefficients of ω^6 and ω^8 to zero). The expression for v_g'/v_g then takes the form $m\sigma/\sqrt{(A+B\omega^{10})}$.

Similarly, if we employ a network containing n elements we can arrange that v_g'/v_g takes the form $m\sigma/\sqrt{(A+B\omega^{2n})}$ and can also satisfy one further condition which will determine the cut-off frequency. The solution is unique, i.e. there is one and only one value for each of the elements. No general solution has been obtained, but it would appear to be real in all cases.

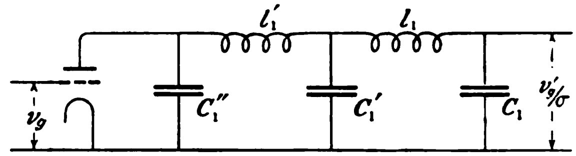


FIG 24.

The arrangement is not a true filter but a device for producing a constant terminal voltage for an input of given magnitude, within certain limits of frequency. It thus fulfils the function of a filter and might be conveniently embodied for this purpose as part of a voltage amplifier. Band and high-pass arrangements are of course as readily devised. No practical work has been carried out on this problem apart from measurements on intervalve transformers having primary capacity.

(B) MEASUREMENTS ON LEAKAGE INDUCTANCE.

The figures for $1 - k^2$ which were calculated from the characteristics shown in Figs. 8, 9 and 10 are uniformly lower than those corresponding to independent measurements made on the transformers. The values of the primary inductances of the transformers were measured in circuit, and those of the leakage inductances were measured by short-circuiting the secondary windings and making a simple bridge measurement of the residual primary inductance. As a result the following figures were obtained :—

Transformer	$1 - k^2$ from characteristic	$1 - k^2$ from measurement
No. 2	0·030	0·053
No. 3	0·017	0·031
No. 4	0·010	0·013

The discrepancy is thus very large, though at the same time the straight-line plots for the values of P gave a strong indication that the theory was basically sound.

With a view to investigating the matter further, some measurements were made on transformer No. 2 with a condenser of value approximately $0 \cdot 0003\ \mu F$ across its

secondary winding, so that the external capacity was large in comparison with the internal capacity. The following results were obtained on a measurement of amplification :—

First resonant frequency = $0 \cdot 615$ kilocycles
Second resonant frequency = $2 \cdot 690$ kilocycles

and from this $1 - k^2 = 0 \cdot 0520$, which is in good agreement with the directly measured value.

It thus appears that the distribution of the capacity of the transformer through the winding controls the effective value of $1 - k^2$. At first it was thought that the discrepancy might be due to the presence of mutual capacity, but this would require a variation of $1 - k^2$ in the opposite sense. The interpretation would seem to be that the effective capacity of the transformer does not embrace the whole of the leakage inductance, so that the representation of the transformer is as shown in Fig. 25.

The effective secondary capacity is here shown as being connected to an intermediate point on the secondary leakage inductance. The addition of a large condenser to this arrangement shunts the whole of the

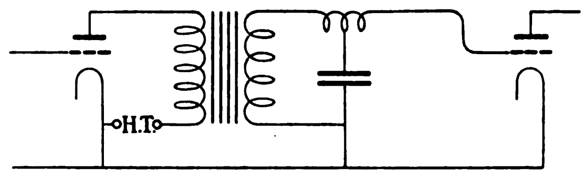


FIG. 25.

secondary leakage inductance by capacity and the normal figures are obtained.

It may further be remarked that measurements on line transformers having a resistance load on the secondary winding give normal results for the values of $1 - k^2$.

DISCUSSION BEFORE THE WIRELESS SECTION, 2 JUNE, 1926.

Mr. P. K. Turner: There is in my opinion a fundamental objection to the bridge method described by the author. A few months ago, when the author described this bridge in connection with another paper, he claimed as one of its great advantages that the transformer was measured under normal working conditions. But I perceive that under the usual conditions of use of this bridge there is no alternating current in the anode circuit of the valve following the transformer being measured. Hence there is no throw-back across that valve. From this it follows that there is no possibility of negative resistance in the input circuit of that valve, and hence the transformer has quite definitely a positive load on its secondary winding. If there were an inductive load in the anode circuit of the valve following the transformer, it is practically certain that the effective load on the transformer would be considerably reduced, with perhaps quite different results on measurement. In everyday use, the valve following the transformer will have in its anode circuit either another transformer or a telephone (or loud-speaker); in fact, there will be in this circuit a complex impedance. Therefore at different frequencies there will be a varying load on the transformer, which will affect its anode impedance and almost certainly its performance. Thus it seems to me that the bridge does not, in fact, fulfil the stated conditions of measuring the transformer under conditions of use. Now that we have received so much information about what one might call the preliminary design of a transformer, I am anxious for even more information. Supposing that by the use of the author's principles of design one has arrived at the point that the primary of the transformer which one proposes to design must be of such and such an inductance, that the magnetic leakage must not be more than a certain small percentage, and that the stray capacities must be below a certain small amount, how does one proceed to design the transformer? What is the permeability of an iron core with laminations of normal thickness under conditions of use in a transformer? I can think of three possible permeabilities, owing to the fact that there is a steady polarizing current in the core. There is the ordinary permeability, B/H, measured at the value of H given by the pure alternating current; there is the same B/H measured at the H given by the polarizing current; and there is the differential permeability, dB/dH, measured about the H given by the polarizing current. With most types of iron these will be widely different from one another. Then, again, what is the effective cross-section of the iron with laminations of normal thickness, i.e. to what extent does the field penetrate into the iron itself at various frequencies? Again, in view of the fact that the transformer works with a high resistance in its primary circuit, what is the comparative importance of transformer losses? I am sure that information on some of these puzzling points would be much appreciated by all of us, and I should like to make it clear that any criticisms which I have made on details of the author's methods do not in any way indicate a lack of appreciation of the very valuable work that he has done.

(*Communicated*): Although it may seem only a minor detail, I should like to comment upon some of the symbols used in the advance copies of the paper, especially the use of ρ* for the internal resistance of the anode circuit. There is a general tendency in physical work nowadays to use small Greek letters to indicate entities which are essentially in the nature of absolute quantities, while using English letters for actual physical quantities: typical of this is the author's own choice of σ for the step-up ratio of the transformer, which is a pure number; and of L and R for inductance and resistance, which are physical quantities. Apart, however, from this general objection, I should like to call the author's attention to the fact that ρ has been officially standardized as the symbol for resistivity, and should therefore not be used for a resistance. The symbol R_a is almost universally used as the symbol for internal differential resistance between anode and filament of a valve. There are other points of termin-

* Corrected for the *Journal*.

ology in the paper to which I should like to refer. For example, immediately under Fig. 2 the author indicates by Z what he calls the "anode impedance," but judging by the analysis which follows, what he really means by Z is the *external* impedance of the anode circuit. Again, in the same sentence he denotes by v_a the "anode voltage", and again the analysis shows that what he means is the voltage developed in the external anode circuit, which is a quite different thing, for "anode voltage" should surely mean the total E.M.F. induced in the anode circuit. Again, on page 1074, and I believe elsewhere, he refers to the "coefficient of coupling," and gives it as 1 per cent.* It seems fairly obvious from the context that he really intends to say that the coefficient of coupling is 99 per cent and that the *leakage* coefficient is 1 per cent.

Mr. H. A. Thomas : I wish to confine my remarks entirely to the method of measurement. My objection to the method is that the output valve is not fulfilling its normal functions. It is not giving the load on the transformer secondary; and, as is well known, the effect of very small impedence shunts across the secondary is very serious. The backing-off valve which is used acts virtually as a shunt to the normal output valve, and the grid of this valve is connected by a large amount of apparatus forming a large input capacity to the other output grid. I have recently tried the effect of this shunting valve as shown in the author's diagram. A Marconi transformer was used with a D.E.R. valve and 100 volts high tension, and a negative grid bias of 4 volts, the frequency being 2 000. The stage amplification with a weak output under normal conditions was found to be 33. A similar valve was connected across the original output valve in the same way as shown in the diagram, and the amplification fell to 28. The connecting grid lead was lengthened to about 1 ft., which I should estimate would be about the length that would be used with the bridge. The amplification fell from 28 to 26·5, showing very clearly that even a small amount of wire will have a very great effect on the amplification. The effect of the capacities of the bridge taken as a whole, not to earth, would increase this fall. Therefore, it seems that the presence of the backing-off valve may produce an error of at least 25 per cent in the determination of the amplification. I should be interested to know what differences the author has obtained with his method when compared with other methods which give normal output conditions.

Mr. H. L. Kirke : The work I have done on transformers has been concerned with input and output transformers for amplifiers used in broadcasting transmission chains rather than intervalve transformers; but some points do actually come into the question in connection with intervalve transformers. The author discusses the series-condenser method of increasing the low-frequency component of amplification in any intervalve transformer system. I have used that method, and I believe that other wireless engineers have used it in various connections, particularly in the case of output transformers, where the output is connected to a line. I have found it very satisfactory indeed, and I have taken care to see, by the use of cathode-ray oscillographs and the like, that there is no distortion whatever. With regard to the question of iron distortion, the point did arise, as I was using transformers at very high flux densities, and the cathode-ray oscillograph showed that there was no appreciable distortion in the iron, provided that a value of B of 5000 per cm^2 was not exceeded. In this connection it is interesting to know that the value of inductance of a transformer, i.e. the effective value of permeability, can vary about 15 to 1, according to the value of flux density in the iron over the range; but, nevertheless, the minimum permeability appears never to decrease below the value of between 200 and 300. Those tests were made with the ordinary inductance bridge, amplifying the output of the bridge in a carefully screened amplifier, and putting various known values of the current into the bridge so that the actual value of H could be calculated. One point brought out in the paper, in connection with the series-condenser method of bringing up the low frequency, is the variation of output impedance due to the condenser and transformer primary forming a series resonant circuit, lowering its impedance about the resonant frequency. That question is of importance, particularly if the input to the valve is large; the dynamic characteristic will vary considerably and so cause distortion. Although it is not actually a point in connection with this paper, the distortion due to the use of reactive output impedance in a rectifier is very interesting. In some forms of rectifiers, particularly the crystal, the effect of input impedance on rectification is dependent very largely upon the low-frequency back E.M.F. If that back E.M.F. is out of phase with the low-frequency current, some curious effects will be noticed. I have noted them on the cathode-ray oscillograph: in one particular case I had a rectifier which should have been perfect, but the oscillograph showed that the results were very far from being perfect. That is due to having a reactive impedance. On making the reactance completely non-reactive, the distortion disappeared completely. The author has pointed out that, by placing a condenser across the primary of the intervalve transformer, he effectively turned it into a low-pass filter. He stated that the value of the condenser should be one-third of the effective capacity of the secondary winding, as shown on the primary. In the ordinary design of electric filter circuits, the capacity of the end condensers, if we use the mid-shunt termination, should be one-half of that of the condensers in the centre. If there is only a single stage with the condenser at each end and one inductance in the middle, the two condensers should be equal. I should be very interested to know why he used the value of one-third, or whether it is merely empirical. With regard to Mr. Turner's point about the value of permeability and how to calculate it, I have done a certain amount of work on that subject, and particularly in regard to the change of inductance due to varying flux through the transformer. I attempted to calculate the inductance which would result by using a static iron characteristic, and I found that the a.c. inductance bore no relation to the position on the static iron characteristic due to d.c. flux. In

* Corrected for the *Journal*.

general the d.c. flux tended to decrease the inductance rather than to increase it. The d.c. permeability of iron often varies from about 200 to 2 000. One would expect a.c. permeability to do the same, if one sets the d.c. flux to that point, but actually in practice it does not do so. I was particularly interested in the author's remarks about inter-electrode feed-back effects, as I have had considerable trouble in this direction in high-power modulation systems, where a number of valves are used in parallel and the inter-valve capacity is relatively large (of the order of 0·0001 to 0·0003 μF). In this case the feed-back effect is to produce a decrease in amplification at high frequencies; in some cases the amplification was reduced to 10 per cent of the maximum. With regard to the curves of transformers published in the paper, I should like to point out that, for good reproduction, frequencies as low as 50 cycles require amplification; and, no doubt, development in efficient transformer design has been considerably delayed by the fact that the average loud-speaker does not reproduce the low frequencies at all (i.e. the frequencies below 200 cycles). I think that future development should be on the lines of an essentially flat characteristic from 50 to 10 000 cycles, which, to my knowledge, cannot be obtained without considerable loss of efficiency.

Mr. C. G. Garton: I think that it is important to obtain as low values as possible in the leakage inductance and self-capacity, but it seems to be quite possible to get a very good design of transformer which has both large leakage inductance and large self-capacity. The curve can certainly be obtained flat to over 5 kilocycles. Can the author say whether he considers there is any great disadvantage in that design? I think that the second resonance point is probably about 6 to 7 kilocycles, rather than 9 to 10 kilocycles, which makes for a larger and more expensive design. But these figures are on the limits of the audio-frequency range, and I do not think the increased cost is justified by the better quality obtained by the author's design. With regard to the question of permeability of iron and the losses therein, so long as the a.c. amplitude is small compared with the d.c. polarizing current, there is no question that the differential permeability is the correct permeability to use. It is practically constant for the whole range of the curve until the saturation point is reached, and, for ordinary iron, ranges between 200 and 400. It is possible to obtain nickel-iron alloys in which the differential permeability reaches values as high as 1 200; but they are prohibitively expensive, unless it is required to make a special transformer for a particular purpose. There is very little difference between the permeability curves for 400 cycles and 50 cycles. I have not gone above 400, but I have found that the permeability is of very little importance above that frequency, because the reactance at 400 cycles is so large that one is not concerned with it but only with the question of iron permeability at lower frequencies. So far as the losses in iron are concerned, they seem to be negligible. As has been mentioned already, the inductance is the determining factor. I was interested also in the question of whether the bridge which is used for obtaining these frequency characteristics should or should not take account of the reaction due to the load in the second valve. My own bridge, an account of which was given in the *Journal*,* received precisely the same criticism. I wish to maintain strongly that these bridges ought to be worked with a second valve and no reaction. It is a sound principle in any investigation to reduce the number of variables as much as possible. If the load, i.e. the measuring valve of any bridge, is to be allowed to vary with the conditions, the characteristic curve obtained is not one for a particular transformer and its associated valve, but for a two-valve amplifier, in effect. Therefore, I think it is a sound principle to use a bridge which eliminates that effect and, if it does not give a practical curve, gives a curve from which something can be deduced, instead of one which is compounded of several different effects.

Mr. C. F. Phillips: Ingenious as the author's bridge arrangement undoubtedly is, from my own point of view it has certain disadvantages. Perhaps the most serious are the elaboration of the apparatus, the time taken in conducting a test, and the amount of arithmetic involved. I should like to indicate a method by which part of the information—the degree of effective amplification per stage—can be measured in a considerably simpler manner. This method has, however, one defect; it gives no information as to the comparative phase of the input and output voltages. It is in essence a variation of the old "slide-back" method, in which an a.c. voltage on the grid of a valve was measured by seeing how much bias was required to reduce anode current to zero. The serious disadvantage was the difficulty of determining just when the anode current became zero. Further, it cannot be used in this case, for the valves would be working under freak conditions. By watching, instead, the grid current, this method becomes quite practical. A galvanometer and potentiometer are inserted in the grid circuit of the valve before and the valve after the transformer, and each grid is biased until the grid current vanishes. Knowing the grid potential for zero grid current with *no* input E.M.F., one has only to observe the "drop" to give zero grid current in each valve under signals, and their ratio is the value of the stage amplification. It is obvious that the measurement is taken under precisely the right conditions for satisfactory amplification, and is therefore a true working test. In conclusion I should like to ask the author what, in his opinion, are the causes of transformer breakdowns.

Dr. R. L. Smith-Rose: It has been very noticeable during the last few years that new-comers to the intervalve transformer industry have, in nearly every case, repeated all the mistakes made by those who preceded them in the manufacture of such transformers. At the present time the available transformers can be divided into two classes, those which are moderately good and those which are bad. The author has gone about the matter scientifically, and has been studying the problem theoretically as well as from a practical point of view, and has thereby arrived at some quite successful results. One point which I should like to raise in connection with his method of testing, or in connection with the results obtained by testing, is the

* *Journal I.E.E.*, 1926, vol. 64, p. 270.

question of the lowest frequency at which he is able to carry out those tests. I understood previously that this frequency was in the neighbourhood of 250 cycles per sec., whereas in every case the curves in the author's diagrams continue down to 100 cycles per sec. Were those results obtained by extrapolation, or were they actual measurements with the bridge in question? Also, with reference to the question raised by Mr. Garton of studying the behaviour of an isolated transformer with no valve or its equivalent load attached, it should be remembered that at the present time the only practical application of intervalve transformers is as the coupling portion of a valve-amplifying stage. A perfect transformer may be produced, but in practice a valve must be connected to it with its associated load; and it is that combination which we desire to give uniform amplification at all frequencies. In the method of measurement described by Mr. Phillips, the only pitfall is the question of the limiting accuracy. The measurement depends upon the detection of the start of the grid current. Since the grid-current/grid-voltage curve meets the axis at a small angle, although not necessarily tangentially, it may be very difficult to determine the exact point at which the grid current commences, and that would place a limiting accuracy on the method. Considering that the transformer employs a closed iron circuit, I was surprised to find on pages 1073 and 1074 that the coefficient of coupling* is stated to be about 1 per cent. Is there not a slip in nomenclature here? The question of the future of the intervalve transformer to be used for reproduction of music appears to require concentrated attention in the direction of lower frequencies. If, instead of employing uniform frequency curves, the results are plotted on the pitch scale, one immediately realizes that the frequency of 250 cycles comes almost in the centre of the important part of the scale of audible frequencies. With frequencies above that limit we are able to obtain transformers with reasonably straight characteristics; but all those transformers show a tendency to fall off at a frequency below 250; and I think they must inevitably pass through zero at zero frequency. It is at the range of frequency between say 16 and 250 cycles that attention is now required, and I should like to obtain opinions as to whether we shall ever get a satisfactory coupling unit as a simple transformer or whether the final solution will not rather lie in the direction of a coupling component, using actual chokes and condensers the equivalent of which we are at present trying to concentrate into the windings of the transformer itself. I think it is possible that the development of such a coupling unit—it does not matter how complicated it is, provided it is put together in a box with just the input and output terminals accessible—will be necessary and more expedient in the very near future. In common with Mr. Phillips, I should like to hear the author's views on the subject of the breakdown of transformers. In this connection Fig. 19 shows one useful way out of the transformer breakdown difficulty by shifting the responsibility on to the choke, which is less expensive to replace; and in the case of a breakdown of the choke one can always use the transformer in its more usual circuit arrangement.

* Corrected for the *Journal*.

Mr. P. W. Willans (*in reply*): I should like to thank the members of the Wireless Section for the kind reception which they have given to the paper and for the remarks of appreciation of the work carried out. The main criticism which has been directed against the work as a whole is that the bridge method does not give a true estimate of the performance of an intervalve transformer under the conditions of operation, and I propose therefore to deal with this point first of all, in reply particularly to the criticisms of Mr. Turner and Mr. Thomas. Here I am very considerably helped by the remarks of Mr. Garton who has been working on a similar method. First of all as far as the measurement of the performance of transformers is concerned we must necessarily employ some standardized conditions, and there is no doubt that if we allow the use of a subsequent valve with an arbitrary impedance in its anode circuit the conditions are the reverse of standardized. We are then concerned not only with the capacity of this valve, which may be regarded as of small account in determining the characteristic (apart from the Miller effect), but we must also consider the magnification factor and resistance of the valve and the nature of the impedance included in its anode circuit. I much regret that the measurements which have been given in illustration of the Miller effect were not available in the advance copies of the paper, but I hope that they give a sufficiently good indication that the bridge method of measurement is quite equal to taking this into account should it be desired to do so; and the fact that the main part of the paper has been written without reference to this effect, and only in connection with the performance of transformers under conditions where it is suppressed, is merely due to the very reasonable desire to make comparisons of transformer characteristics and constants under unvarying conditions. I cannot put this point better than it has been put by Mr. Garton in the latter part of his remarks.

With regard to Mr. Turner's further comments, some of the points he raises have been dealt with in the text of the paper, in particular the question of the permeability of the iron under the conditions of operation. This I estimated as having a value between 200 and 300 (cf. page 1072, col. 2), and I note that Mr. Kirke and Mr. Garton both give values which substantially confirm my own. This permeability is of course the differential permeability at the points on the *B-H* characteristic corresponding to the value of the polarizing current under working conditions. For normal voltage-amplitudes this may be regarded as constant, though for high amplitudes at low frequencies there may be a deviation from this value, in general an increase. Mr. Garton has mentioned other types of iron, in particular nickel-iron alloys, and I can confirm the values of differential permeability which he gives, as also the question of expense.

With regard to the effective cross-section of iron, the work carried out does not give full information on this point, but it does give the practical information that the transformer can be regarded, between certain limits of frequency, as having a substantially constant

inductance at low flux densities. I would estimate these limits as between 250 and 1 000 cycles per second; at the higher frequencies the inductance may quite well fall off in value without this change being apparent from the transformer characteristics, since the inductive impedance is so very much higher than the capacitative impedance. For values below 250 cycles I have no measurements which are sufficiently reliable to give any indication. The leakage inductance of a transformer appears to rise slightly at the lower frequencies, but here its effect is not very great. From 1 000 cycles upwards it may be considered to have a constant value; but this is only natural, since one would expect the flux through the core to thread both windings and, in consequence, the leakage inductance to depend only upon the geometrical arrangement of the coils.

Mr. Turner's point regarding transformer losses has been dealt with on page 1074 of the paper. These are negligible in any transformer of good construction unless there are short-circuited turns in the windings.

In reply to Mr. Turner's criticisms regarding the symbols used, I have only apologies to offer. I assure him that I will endeavour to "think internationally" in future. I have modified the text of the paper so as to meet his criticisms as regards the definition of Z and any lack of clarity there may have been as to what was meant by "anode voltage." The leakage of the transformer is of course 1 per cent and not the "coefficient of coupling," although I should like to mention, in passing, that if $1 - k^2 = 0 \cdot 01$ the value of k will be $0 \cdot 995$.

In reply to Mr. Thomas's criticisms, I have already dealt with the use of the bridge in relation to the Miller effect. With regard to his criticism of the method of measurement, I cannot agree that the "backing-off" valve, which I assume is the valve B′ in Fig. 3, acts virtually as a shunt to the normal output valve. It is quite clear from the manner in which the bridge is used that at the point of balance the plates of the valves B and B′ are at steady potential in relation to their filaments and also, by virtue of the Wagner balance, in relation to earth. It would seem that, provided the Wagner principle is properly applied, there is no possibility whatever of induction from one grid to the other through the plates of the valves. The effect of the large amount of apparatus, e.g. batteries and the like, is admittedly very serious unless a proper Wagner balance is employed; I have tried to use the bridge without the Wagner arrangement and obtained extremely inconsistent results, which resemble those described by Mr. Thomas. I admit that if an impedance be inserted in the anode circuit of the output valve and no trouble be taken to balance the bridge in the manner described, the load on the transformer may vary enormously and all sorts of discordant results be obtained. Without further knowledge of the exact conditions of Mr. Thomas's measurements I cannot suggest any explanation for his results, but I can assure him that the amplification of transformers is so closely in agreement with theory that there is not the slightest chance of an error as serious as 25 per cent. I have made no actual comparisons with other methods but have placed reliance on this agreement with theory, and I suggest that, if a comparison between any two methods is being made, the bridge be set up in exactly the manner described and an attempt be made to measure the input and output voltages of the stage of amplification at the same time. I regret that my resources have not been sufficient to make a really good comparative test on this point, and it would be of interest if Mr. Thomas or any other worker who has similar resources at his disposal could make a really satisfactory comparison. At the same time I feel that there must certainly be something wrong in the tests which he has so far carried out, and I venture to suggest that some consideration of the points above outlined may result in an explanation of the discrepancies experienced.

Mr. Kirke's remarks regarding the work which he has carried out on line transformers are of the greatest interest. These transformers are employed in circuits which are characterized by the presence of a load on each winding, and under practical conditions their self-capacity is so low as to be negligible. The result is a great predominance of the virtual capacity term due to losses and leakage and, in consequence, a state of affairs where it is difficult to get adequate reproduction of the lower frequencies without a cut-off at the higher frequencies. Mr. Kirke's success in this respect is of course well known. There seems to be some slight confusion regarding the question of amplitude distortion in the series condenser circuit, as Mr. Kirke alludes to the variation of output impedance due to the condenser and transformer primary forming a series resonant circuit, which of course is the principle underlying the method whereby an accentuation of the lower frequencies is obtained. My contention was that if the input to the valve varied, the effective inductance also varied, and the anode circuit impedance in consequence became a function of the amplitude. Mr. Kirke appears to put this in other words by saying that the dynamic characteristic will vary considerably and so cause distortion. Such distortion would appear to me to be inevitable at some low frequency and, in view of the amplification rising to a high peak value in the series condenser circuit, I consider the latter is more prone to give variations in the dynamic characteristic than a simple transformer. This defect is not found in the reaction circuit described in the paper. Mr. Kirke's notes on the subject of rectifiers are of great interest; I have noticed that a condenser and leak in series with the grid of an amplifying valve produce quite a definite change in the amplification of the transformer following it. With regard to the filter-circuit question, I am afraid that this was dealt with in a very inadequate manner when the paper was read and I have therefore elaborated it somewhat in the Appendix. The point really is that the arrangement is strictly not a filter at all but only analogous to one, in that it is a device for producing a constant voltage across a given terminal impedance when the input impedance is a resistance of given value. The value of one-third is based entirely on theoretical considerations, as appears from the analysis given in the Appendix. Mr. Kirke notes the necessity for the adequate reproduction of really low frequency, and this point is also mentioned in Dr. Smith-Rose's criticisms. I have dealt with this question later in my reply.

In reply to Mr. Garton I am bound to say that I consider it advisable to have the high value of second resonance which was specified, as I believe that under these circumstances the transformers work better in combination with each other whether the neutrodyne method be used or not. If a neutrodyne connection is employed, low leakage inductance is essential in order to get adequate neutralization with valves of high magnification factor, and it is definitely possible to employ such valves without loss of quality. If no neutralization be used it is necessary to reduce the step-up ratio of the transformer, and in this case the effect of the reaction from a subsequent stage of amplification will be to reduce the extent of possible straight characteristic by steepening the drop of P. I feel very strongly that there is a necessity for a margin of straight characteristic over and above what might be regarded as the upper limit of practical audio frequency in order that there may be something in hand when the transformers are worked in association with each other. With the remainder of Mr. Garton's remarks I am in entire agreement, and the points he raises have already been dealt with.

Mr. Phillips's criticisms of the bridge method on the grounds of the difficulty of working it are, I think, unjustified. I admit that the arrangement looks somewhat terrifying in the form of a circuit diagram, but in practice it is readily possible to take, say, six observations of a transformer amplification curve in the space of 20 minutes or so, and the reduction of these results when reduced by a rule-of-thumb process is very speedy indeed. Furthermore, the possibility of extrapolating the results and of deducing what is going on in the circuits under consideration, to my mind far outweighs any preliminary difficulties in getting acquainted with the routine of working the apparatus. With regard to Mr. Phillips's suggested method, I share Dr. Smith-Rose's mistrust of the slide-back principle, particularly in view of the possible damping effect of grid current. I have used slide-back methods in the past and have found the observation of the " end point " an extremely difficult and nerve-racking matter, and it would seem barely worth while to place reliance on such a method now that the thermionic voltmeter has reached such a satisfactory state of development. A possible source of error in all methods of this kind may be worth mentioning, namely, that due either to bad wave-form of the input frequency or to the generation of harmonics in the circuit under test. The bridge method has the advantage of isolating one frequency in what is possibly the simplest of all manners. With regard to Mr. Phillips's question on the subject of transformer breakdowns, which are also alluded to by Dr. Smith-Rose, I fear that I have no useful information to give, though I believe that with the transformer under discussion a satisfactory method of impregnating the windings has been arrived at and breakdowns now no longer occur. Unfortunately, as I was no longer connected with this work when the trouble of breakdowns arose, I have not had any experience in this respect and can therefore make no useful contribution to the question.

In reply to Dr. Smith-Rose, the measurements down to 100 cycles per second are extrapolated, though I see no reason why the bridge method should not be applied to such frequencies if a vibration galvanometer is substituted for the telephones. I appreciate that we have to consider the effect of a loaded transformer, but I submit that the use of the neutrodyne renders the associated load practically negligible at the important audio frequencies, and that we may consider this combination just as well as any other in dealing with the transformer problem. Apart from the question of neutralizing, there is no question to my mind that a transformer which is good when unloaded is also good when loaded. The nomenclature as regards the coefficient of coupling was of course a slip and has been rectified for the *Journal*. Dr. Smith-Rose's remarks on the importance of low frequencies are of great interest, though as a result of comparisons between resistance and transformer amplifiers I would not agree that the frequencies below 250 cycles are of as great importance as the frequencies above this limit. I am considering now purely the æsthetic aspect of broadcast reproduction, and I can only explain this by the fact (for so it appears to me) that if we are enabled to reproduce all the harmonics of a given tone in an adequate manner we get psychologically a large measure of the effect of the fundamental note. I believe that experiments have established this to a remarkable degree. However, there is no doubt that the lower frequencies have great importance as far as naturalness of certain tones is concerned, and I quite admit that the transformer in question, in common with nearly all others, leaves a considerable amount to be desired in this respect. I believe, all the same, that there is great hope in the correct application of the low-frequency reaction principle to supplement the lower frequencies, on the lines of the circuit which has been described in the paper.

THEORY OF OVERLAPPING JOINTS.*

By Raymond M. Wilmotte, B.A.

[From the National Physical Laboratory.]

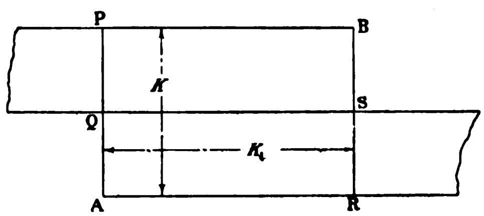
(*Paper received 4th March, 1926.*)

Summary.

Melsom and Booth have investigated experimentally the theory of overlapping joints, dividing the resistance of the joint into two parts: one representing the resistance due to the contact, and the other that due to the stream lines of the current at the joint. In the present paper the latter part is obtained theoretically in terms of elliptic functions. The result is expanded and leads to a very simple formula, with which the experimental results of Melsom and Booth are found to agree.

In a paper presented in 1920 to the Institution † S. W. Melsom and H. C. Booth described an experimental investigation of the efficiency of overlapping joints. They divided the resistance of a joint into two parts, one representing the resistance due to the stream lines of current at the joint and the other that due to the contact, and assumed that the two could be added arithmetically.

The second part cannot be estimated mathematically, but the first can be readily obtained and is reducible,



in practical cases, to a very simple formula. Melsom and Booth estimated the first part by cutting a piece of tinfoil to the shape of the joint and measuring the potential difference across the joint when a known current was flowing. They expressed the efficiency of the joint as the ratio of the potential difference across the joint to the potential difference across an equal length of one straight conductor. This they called σ. When the joint is infinitely long, σ obviously tends to the value $0 \cdot 5$.

The resistance of a rectangular conductor with any electrodes along the edge is readily obtained by Schwarz's transformation ‡ of conformal representation.

In the case of an overlapping joint, we shall obtain a lower limit to the resistance if we assume that PQ and RS (see diagram) are equipotentials. When the overlap is long compared with the thickness, as it invariably is in practice, this lower limit will be very nearly the true resistance required. Let $\frac{1}{2}K$ be the thickness of each conductor and K_1 be the length of the overlap; then it can be shown that the resistance of the joint is given by

$$2\sigma = \frac{KL_1}{K_1 L} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where L_1, L, are the complete elliptic functions of the second kind of modulus $\sqrt{(1-l^2)}$, l respectively, given by

$$l^2 = \tfrac{1}{2}[1 - \sqrt{(1-k^2)}]$$

and the complete elliptic functions of the second kind of modulus k, $\sqrt{(1-k^2)}$ are K, K_1 respectively.

In practice, $K_1 > K$, so that k and l will be small, and we can write

$$K = \tfrac{1}{2}\pi(1 + \tfrac{1}{4}k^2 + \ldots)$$

$$K_1 = (1 + \tfrac{1}{4}k^2 + \ldots)\log_e\left(\frac{4}{k}\right) - \frac{k^2}{4} + \ldots$$

These two equations give

$$k = 4x\,(1 - 4x^2 + \ldots)$$

where $x = e^{-\frac{1}{2}\pi\rho}$ and $K_1/K = \rho$

Therefore $l^2 = 4x^2(1 - 4x^2 + \ldots)$

and finally, expanding L and L_1 in terms of l, we have

$$2\sigma = 1 + \frac{2}{\pi\rho}\log_e 2 + \frac{2}{\pi}e^{-\pi\rho}$$

$$= 1 + \frac{0 \cdot 441}{\rho} + 0 \cdot 636e^{-\pi\rho} \quad . \quad . \quad . \quad (2)$$

The last term in this equation is small and can be neglected in practical cases.

In the following table the values of σ are given for various values of ρ, and are compared with the experimental values of Melsom and Booth.

2ρ	σ calculated	σ observed
1	1·01	1·10
2	0·72	0·74
3	0·65	0·63
4	0·61	0·59
5	0·58	0·56

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1922, vol. 60, p. 889.

‡ H. F. Moulton: *Proceedings of the Mathematical Society*, 1905, vol. 31, p. 104.

These values are obtained from equation (2), which is only approximate. Thus the true value of σ, calculated from Legendre's table for $2\rho = 1$, is $1 \cdot 12$, which is very close to the observed value. When $\rho > 1$, equation (2) will give a very close approximation.

When there is a contact resistance between the two conductors the lines of flow will be altered at the junction. This alteration increases with increasing contact resistance. The percentage error in assuming, as Melsom and Booth did, that the lines of flow were unaltered, will therefore not be large, for the effect of σ on the efficiency of the joint decreases as the contact resistance increases.

THE PRODUCTION OF FLICKER IN ELECTRIC LAMPS BY CYCLIC IRREGULARITY IN THE VOLTAGE.*

[REPORT (REF. Z/T22) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

INTRODUCTION.

This investigation was undertaken at the Faraday House Testing Laboratory to ascertain the limits observable by the human eye of cyclic irregularity in the voltage of the supply to electric incandescent lamps.

An investigation has been carried out by K. Simons † which tends to show that the eye is most sensitive to flicker occurring with a periodicity of about 6 cycles per second. It is also shown that the percentage variation of light which can be detected by the eye decreases with large increase of intensity of illumination.

SCOPE OF RESEARCH.

The following was the scope of the proposed investigation :—

(*a*) Tests to be made with cyclic irregularity having a frequency of 0 to 15 cycles per second, and therefore covering the most sensitive region, as shown by previous investigators.

(*b*) It was suggested that the test be made with a d.c. supply, the voltage pulsation being superimposed either by means of an a.c. transformer or a crank-driven sliding-contact rheostat.

(*c*) A test to be made in the first place with an ordinary 50-watt 200-volt metal-filament lamp.

(*d*) It would be necessary to establish provisionally a limit of flicker. The limit may vary with the investigator, and it would be desirable to test two or three observers to ascertain what extent of agreement there would be as to the point at which the flicker disappeared. If there were no clear limit, it would be necessary to adopt an arbitrary limit, as, for example, a negligible (though observable) amount of flicker produced by a certain percentage voltage fluctuation at a given frequency with, say, the above lamp, and to make a direct comparison of this degree of flicker with that obtained under other conditions.

(*e*) As the observable flicker varies with the illumination, it was suggested that flicker be observed on a white surface with clear black print illuminated by bringing the lamp within, say, 18 in. of the surface, as might be done by a draughtsman.

(*f*) The same investigation should be repeated in sufficient detail for purposes of comparison with :—

(i) a low-voltage thick-filament lamp,
(ii) a high-voltage gas-filled lamp.

METHOD OF SUPERIMPOSING VOLTAGE PULSATIONS.

The lamp under test was run from a steady d.c. supply, and the voltage pulsations were superimposed by two methods in turn, namely :—

(i) by means of an a.c. transformer, and
(ii) by means of a crank-driven sliding-contact resistance.

Owing to the great difficulty of measuring accurately at very low frequencies the small a.c. voltages required, the first method was discarded after a considerable amount of unsuccessful experimenting.

The second method, using a crank-driven rheostat, was more successful and was finally adopted as being the more practical. All the results given were obtained by this method.

DESCRIPTION OF APPARATUS.

An ordinary sliding-contact resistance was so arranged that the slider could be oscillated backwards and forwords at any frequency between 0 and 15 complete oscillations per second by means of a connecting rod and crank on the end of a motor shaft. In order to make the

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† *Elektrotechnische Zeitschrift*, 1917 vol. 38, pp. 453, 465 and 474.

motion of the slides approximately simple harmonic, the length of the connecting rod was made about 6 times the length of the stroke. The rubbing-contact springs or brushes were very stiff laterally (i.e. in the direction of motion of the slides) so that distortion due to large accelerations at the higher frequencies was reduced to a minimum.

The Circuit.

It was desirable to be able to vary the superimposed fluctuating voltage continuously without causing any appreciable change in the average voltage applied to the lamp under test, and for this purpose the circuit shown in Fig. 1 was used. The crank-driven resistance

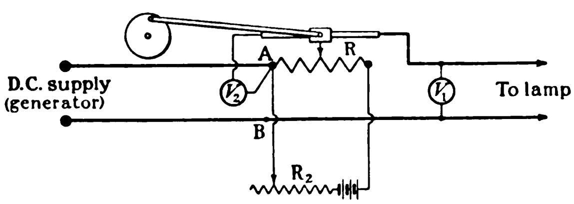

Fig. 1.—Diagram of connections.

R was connected through the slides in series with the lamp in the ordinary way. Across the ends of the resistance R was shunted an auxiliary circuit as shown, thus giving a potentiometer effect. The current through the auxiliary circuit could be varied at will, thus giving any desired voltage pulsation at R. The whole of the apparatus except the lamp and the regulating resistance R_2 was placed outside the dark room.

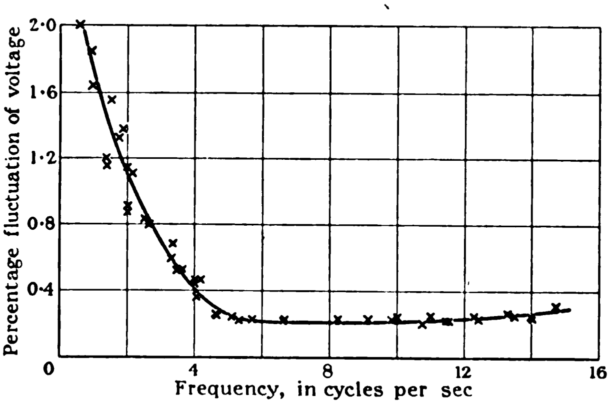

Fig. 2.—Relation between frequency and percentage fluctuation of voltage for negligible amount of flicker. 30-watt, 200-volt vacuum lamp.

While an observation was being made an assistant kept the average voltage V_1 constant and determined the speed of the motor. The frequency was kept constant and the voltage pulsations were varied in amplitude by the observer himself, and when he had found the position on R_2 which gave a limit of visible flicker the motor was stopped and the two values of V_2 read, with the slider of R at each end of the stroke respectively. The total voltage pulsation is given by the difference of these two readings. The main supply to the lamps was taken from a d.c. generator, and the voltage was varied by operating on the field so that the resistance of the circuit could be kept low. No voltage variation could be detected across A B on moving the slider of R.

The lamp under test was in each case placed 18 in. from a sheet of white paper 20 in. × 26 in. containing black print. The eye seemed more sensitive to flicker and the limit was more definite when the illuminated

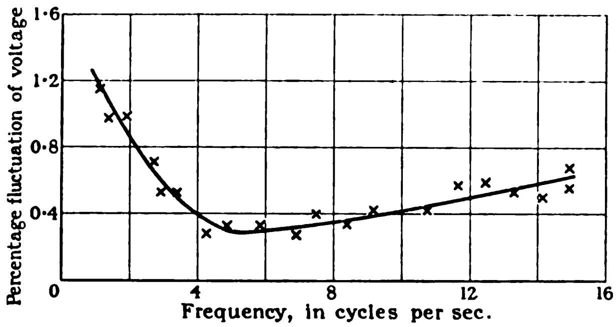

Fig. 3.—Relation between frequency and percentage fluctuation of voltage for negligible amount of flicker. 30-watt, 50-volt vacuum lamp.

surface was viewed from a little distance. In all cases the screen was observed from a distance of 6 ft. The direct rays of the light from the lamps were shaded from the face of the observer.

As would be expected, it was noticed that when the observer looked at the middle of the screen the flicker disappeared there some time before it disappeared at the corners; then, again, on looking at one corner of the screen, although no flicker was noticeable there, it could be easily discerned, by indirect vision, on the centre

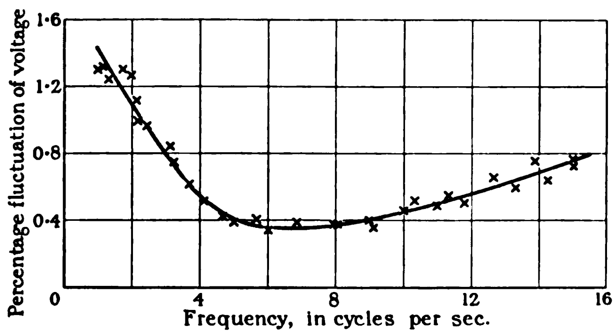

Fig. 4.—Relation between frequency and percentage fluctuation of voltage for negligible amount of flicker. 100-watt, 200-volt gas-filled lamp

and other parts of the screen. In these observations the screen was viewed in the middle, and the amplitude of the voltage pulsations was gradually reduced until the flicker was only just noticeable on the edges and corners of the screen. In determining this limit the degree of uncertainty seemed to vary considerably with the frequency and the type of lamp. In some cases the limit was quite sharply defined and two observers agreed remarkably closely and consistently. On the other hand, especially at frequencies below 3 cycles per second, it

was found most difficult to establish a limit; in the curves of Figs. 2, 3 and 4 all the points have been shown and the degree of uncertainty can be judged.

Tests were first carried out on an ordinary vacuum

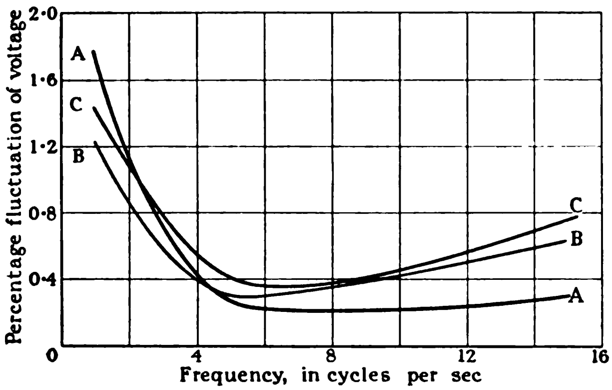

FIG. 5.—Relation between frequency and percentage fluctuation of voltage for negligible amount of flicker.

Curve A.—30-watt, 200-volt vacuum lamp.
Curve B.—30-watt, 50-volt vacuum lamp.
Curve C.—100-watt, 200-volt gas-filled lamp.

lamp rated at 30 watts and 200 volts, and in Fig. 2 a curve is given showing the relation between the frequency and total percentage voltage fluctuation for a negligible amount of flicker. Figs. 3 and 4 give the same relations for a 30-watt 50-volt vacuum lamp and a 100-watt 200-volt gas-filled lamp respectively.

In all cases the total fluctuation is given as a percentage of the average pressure applied to the lamp, viz. :—

$$\text{Percentage fluctuation} = \frac{\text{Max. volts} - \text{Min. volts}}{\text{Average volts}} \times 100$$

In order to facilitate comparison the three curves of Figs. 2, 3, and 4 have been redrawn to the same scale on one sheet (Fig. 5), but in this case the points have been omitted.

CONCLUSIONS.

The investigation, as far as it goes, confirms Simon's conclusion that the eye is most sensitive to flicker at a periodicity of about 6 cycles per second.

Between the limits of frequency of 6 to 10 cycles per second, which is within the limits of speed of gas engines, it will be observed that the percentage fluctuation of voltage should not be more than 0·2 per cent, equivalent to a cyclic irregularity of 1/500.

It has been contended in some quarters that the limit laid down in the present B.E.A.M.A. Standardization Rules of 1/150 for such engines is unnecessarily exacting, but this Report furnishes no support to the contention. In the light of previous work which showed a logarithmic relationship between the percentage variation of light which can be detected by the eye and the intensity of illumination, it is seen that the result obtained would not have been different in character with any reasonable reduction of the illumination of the observed surface, and, whilst the investigators have deliberately taken an unfavourable case for test, the conditions are nevertheless not abnormal.

THE JUBILEE OF THE TELEPHONE.

The Institution celebrated the Jubilee of the Telephone on Thursday, the 24th June, 1926, the nearest convenient date to the anniversary of its submission to the International Jury by its inventor, Alexander Graham Bell, at the Centennial Exhibition at Philadelphia, U.S.A., on the 25th June, 1876.

Luncheon.

The proceedings were inaugurated by a luncheon at the Hotel Cecil, London, which was attended by, among others :—Mr. R. A. Chattock (*President*) in the chair, The Rt. Hon. Sir William Mitchell-Thomson, Bt., K.B.E., M.P. (*Postmaster-General*), The Rt. Hon. Lord Gainford, P.C., D.L., Sir Ernest Rutherford, O.M., F.R.S. (*President, Royal Society*), Sir Oliver Lodge, D.Sc., F.R.S. (*Hon. Member*), Sir William Henry Ellis, G.B.E. (*President, Institution of Civil Engineers*), Sir James Devonshire, K.B.E. (*Vice-President*), Sir E. Manville, Sir Alexander Roger, Mr. B. O. Anson, Mr. Ll. B. Atkinson (*Past-President*), Major B. Binyon, O.B.E., Mr. A. C. Brown, Col. C. B. Clay, Mr. W. W. Cook, Mr. H. Cooper, Mr. W. J. Crampton, Col. R. E. B. Crompton, C.B. (*Hon. Member and Past-President*), Mr. W. M. Crowe, Mr. W. Cruickshank, Mr. R. A. Dalzell, C.B., C.B.E. (*Director of Telegraphs and Telephones, G.P.O.*), Dr. W. H. Eccles, F.R.S., Lieut.-Col. K. Edgcumbe (*Vice-President*), Mr. C. F. Elwell, Prof. J. A. Fleming, M.A., D.Sc., F.R.S. (*Hon. Member*), Prof. C. L. Fortescue, O.B.E., M.A. (*Member of Council*), Mr. R. Grierson (*Member of Council*), Mr. H. H. Harrison (*Past-Chairman, Mersey and North Wales Centre*), Major E. O. Henrici, R.E. (ret.) (*Member of Council*), Mr. J. S. Highfield (*Past-President*), Mr. J. H. Holmes, Mr. F. Hope-Jones, Mr. J. H. Jeans, M.A., D.Sc., F.R.S. (*Secretary, Royal Society*), Mr. W. Judd, Mr. J. E. Kingsbury, Mr. F. Laidlaw, Major A. G. Lee, M.C., Mr. T. D. Lockwood, Col. H. G. Lyons, D.Sc., F.R.S. (*Director, Science Museum*), Senatore G. Marconi, G.C.V.O., LL.D., D.Sc., Mr. W. M. Mordey (*Past-President*), Mr. S. R. Mullard, Lieut.-Col. W. A. J. O'Meara, C.M.G. (*Past Engineer-in-Chief, G.P.O.*), Mr. A. Page (*Vice-President*), Mr. W. H. Patchell (*Past-President, Institution of Mechanical Engineers*), Mr. R. W. Paul (*Member of Council*), Mr. G. F. L. Preston, C.B.E. (*Past-Controller, London Telephone Service*), Mr. J. C. W. Reith, Mr. G. Mure Ritchie, Mr. E. S. Ritter, Dr. Alex. Russell, M.A., LL.D., F.R.S. (*Past-President*), Mr. E. H. Shaughnessy, O.B.E. (*Member of Council*), Mr. Dane Sinclair, Mr. Roger T. Smith (*Past-President*), Mr. C. P. Sparks, C.B.E. (*Past-President*), Mr. F. Tandy, Mr. W. J. Thorrowgood, Mr. J. M. G. Trezise, Mr. W. A. Valentine (*Controller, London Telephone Service*), Mr. H. Laws Webb, Mr. W. B. Woodhouse (*Past-President*), and Mr. P. F. Rowell (*Secretary*).

After the Loyal Toasts had been duly honoured,

The President (Mr. R. A. Chattock) said :—" As members of the Institution, we celebrate to-day the Jubilee of that remarkable invention the telephone, which was born 50 years ago and, in the intervening period, has transformed the daily life of all civilized peoples. Alexander Graham Bell, a native of Edinburgh, but at the time of his invention a citizen of the United States, succeeded in devising instruments for the electrical transmission of speech, and in March, 1876, was granted a patent which was judicially pronounced as introducing a new art to the world. Bell's success, where so many others had failed, must be largely attributed to his environment. His interest in speech and the analysis of speech sounds arose from his association in the work of his father, who was a teacher of elocution. His electrical studies were undertaken primarily as a means of solving some of his acoustic problems. Together they resulted in designs for multiple telegraphy and eventually the telephone itself. The telephone, as a development of telegraphy, naturally aroused the greatest interest in our Institution, which was then the Society of Telegraph Engineers, and amongst our most valued records we count the paper read by Bell himself before the Institution on the 31st October, 1877. From this paper can be seen how Bell realized that before transmission and reproduction of speech could be achieved it was necessary to produce electrically the equivalent of aerial sound waves. This was Bell's primary discovery, and it was its application into instrumental form which constituted the invention. Once the transmission of speech was proved to be possible, subsequent developments were in the nature of improvements and of secondary value. There have been many developments, and the names of Edison and Elisha Gray at once suggest themselves in this connection. I propose, however, to refer to only one development, namely, that due to one of our members, Prof. Hughes, whose discovery of the microphonic effect was immediately applied to telephonic purposes and, as the microphone transmitter, has played so great a part in telephonic development. Hughes's work in this and many other lines is recorded in our *Journal*, as are many of the subsequent developments in the telephone itself and its allied appliances. To-day we pay homage to Bell's memory as one who was not only an inventor but also a discoverer, and whose application of his discovery to the useful arts has made the world so greatly his debtor. We could not have our celebration of this Jubilee either on the anniversary of the first telephonic conversation or on that of the acceptance of the patent, but to-day is as near as we have been able to arrange to a day fraught with great importance to the new instrument and not without its interest to ourselves, for it was on the 25th June, 1876, that Lord Kelvin, then Sir William Thomson, in his capacity as a juror at the Philadelphia Exhibition, had this new invention submitted to his notice. He realized at once its remarkable

nature and its possible utility. Undeveloped as the instrument then was, he appreciated its essentials, and there and then declared that, before long, friends would whisper their secrets over the electric wire. The enthusiasm which the telephone aroused in Sir William Thomson found immediate expression, and was continued throughout his life. His encouragement was of great value to Bell and did much, I think, to promote the development of telephony, for until that day very few, if any, other than Bell himself recognized the potentialities of the new instrument. That day the telephone was introduced to a larger world. It was only an instrument, but an instrument hitherto believed impossible of attainment—an instrument that talked. That instrument remains to-day almost identical in form with the original invention. Bell also conceived that interchange of talks which has since been realized as a telephone exchange. I have no toast to propose, and therefore there will be no responder to my remarks, but I am going to ask the Postmaster-General, as the head of the Post Office which is responsible for our telephone service and our telephonic development, to address us. No one realizes more clearly than Sir William Mitchell-Thomson the value of the telephone service to the community, or its great importance as an aid to industrial efficiency. I have alluded to the extreme simplicity of the telephone as an instrument. On the other hand, it is impossible to exaggerate the complexity of that which forms a telephone system as a whole, and the skill which is called for in its personnel and management, and we welcome the Postmaster-General amongst us, not only for himself, but also as the head of a highly-trained organization undertaking national work of vast importance."

Sir William Mitchell-Thomson, Bart., K.B.E., M.P. (*Postmaster-General*) said: "I have to thank you and the President for the honour which you have done me in inviting me to be here to-day to take part in this auspicious celebration. I have no intention of anticipating an address which Sir Oliver Lodge is to deliver later in the day, but at the same time I could not help reflecting, while the President was speaking, that it is perhaps a coincidence that it should fall to another native of Edinburgh to be present in an official capacity along with his officers to celebrate the Jubilee of the Telephone. I am glad to be here as an outward and visible sign of the interest which the Post Office takes in these celebrations. We have been glad to do what we could by lending apparatus for exhibition purposes. In the Science Museum will be seen the model of the first Bell telephone and also an illustrative practical working model of the very latest type of automatic exchange. When we look from one to the other I confess that although, as the President said, the instrument remains in essentials the same, there is an amazing technical growth. I sometimes think, in looking back over the last half century, that the telephone deserves to be ranked among the greatest contributions, if not the greatest, of science to industry. It is hardly too much to say that the telephone has now become a practical necessity of civilized life. In this country, perhaps, we have not got quite as much of that practical necessity as I should like to see and hope to see, but we are getting on. Last year we installed as many telephones as were installed during the first 20 years of development. At the present moment there are about 1 430 000 telephones in the country, and the number of effective calls for last year was over 1 000 million. We are pushing on with the development of the underground trunk system and also with the development of rural telephones generally. In the last three years we have had something like 800 rural telephone exchanges. This Jubilee year of the telephone coincides with a number of interesting events in connection with telephone development. In the first place it will, I hope, coincide with the installation and completion of the first large automatic exchanges. It will, in the second place, coincide with a deliberate and co-ordinated effort to improve international European telephone facilities generally. At this moment—and that is the reason why the Chief Engineer of the Post Office cannot be here to-day—a conference is being held in Paris for that purpose.* There has just been completed a new submarine cable to Holland with 12 speech channels, which will bring the cities of Germany into complete telephonic touch with this country. Later in the year a new cable is being laid to France with 21 speech channels, and a similar one later to Belgium. The third event—and it is a great event—in this Jubilee year is that, for the first time, our experiments have reached such a stage that ordinary two-way transatlantic telephony has come well within sight. For the moment our experimental work, owing to the coal shortage, has had to be suspended, but we are taking part now in the birth of a great new branch of the science of telephony and I hope that, when our present difficulties in the coal industry are at an end, we shall be able to resume those experiments and bring them to a successful conclusion. I said a moment ago that we were more backward in this country in telephone development than I liked to see. It is not altogether our fault. The telephone in this country had a somewhat chequered career at the start. Then, just in the most critical stage of its development when the nation had taken it over, there came the great war which put an end to the reconstruction that was about to take place and left us with a vast legacy of arrears which we are only just overtaking. I think the efforts which the Post Office is making to improve and develop the telephone system are being appreciated by the community. I am perfectly certain that before long the growth of telephone development in this country will show that the public realize and appreciate the value of improved service. At all events, in that very lively hope I, and all my officers, work, and it is because we believe in the telephone and its advantages and in the possibility of its development, and because we want to see this country taking a place amongst the great telephone-using nations in the world—a place that she

* I learn since that I ought to have given credit for this effort to the Institution of Electrical Engineers, for it was in the Presidential Address to the Institution delivered on the 2nd November, 1923, that attention was called to the urgent necessity of treating international telephony on a unified basis, and of three definite proposals then made, one was that the operating telephone authorities should form an association for this and other matters, and that an early International Conference should be held to initiate the matter.

In March, 1923, an international meeting took place in Paris, at the invitation of the French Government, expressly to consider these proposals, and the existing Comité Consultatif International is the direct and immediate descendant of that meeting. W. M.-T.

ought to take—that I am particularly glad to be here to-day."

Presentation of Faraday Medal.

At 2.45 p.m. in the Lecture Theatre of the Institution, the Faraday Medal was presented to Col. R. E. Crompton, C.B.

The President: On behalf of the Institution I am going to ask Colonel Crompton to accept the Faraday Medal as a mark of our appreciation of his life-long work in the interest of electrical engineering. It is the particular wish of the Council that there should be no suggestion of any intrinsic value in the Medal itself; it is made of bronze and not of gold; it owes its value first of all to the fact that it was instituted to commemorate the foundation of the Institution, and secondly that it is offered for world-wide services to electrical science and engineering. The Council hope that, as time proceeds, the importance of the Medal will be enhanced by the names of its illustrious holders. I will ask Mr. Woodhouse to say a few words.

Mr. W. B. Woodhouse: Every now and then in the field of human endeavour we find a new worker, a man of genius who not only throws a light on the dark places in which he works himself to help progress but who, by his example and by his great and striking personality, encourages all other workers in the field. When the spark of genius which illuminates new problems is accompanied by the persistent and continuous energy necessary to bring the results into the field of practical use, then we have indeed an exceptional type of man. We are here to-day to pay honour to Col. Crompton, a man of that very striking type. The country to which such a man belongs must be proud of him. The age in which such a man appears is blessed in having his energies turned to works for the improvement of methods and for the help of mankind, and those who work in the same field are greatly privileged to know him. Col. Crompton combines many great qualities—the spirit of invention which begins a thing, the diligence and energy and the capacity for taking pains by which the work can be brought into the practical field, and, perhaps the rarest of all in a man with scientific attainments, the common sense and the judgment by which he can make these things commercial and available in the everyday affairs of life. I do not propose to review the work that Col. Crompton has done, because it is well known and is recorded in our *Journal* and in the proceedings of other learned societies. I think, however, that we must not forget, as electrical engineers, that Col. Crompton is distinguished not only in our own particular field but in many other fields as well. He became a Member of this Institution in 1877, was President first in 1895 and again in 1908, and in 1923 was made an Honorary Member. We have heard to-day something of the wonderful progress of the telephone, but I think the progress of the electricity supply industry has been in its way just as wonderful, and we must remember that a very large part of that progress has been due to the work of Col. Crompton. In the very earliest days he devoted his attention to the use and development of electricity for lighting and, later, for other purposes. He invented one of the most successful arc lamps, and subsequently modified entirely the design of the dynamo of that day. I think we may say that he improved everything which he touched. He invented the term "load factor" and immediately proceeded to improve it. He invented the potentiometer, which enabled us accurately to measure things that were formerly guessed at. Throughout he has combined highly technical, constructional and commercial abilities. He was the first, I think, to teach us how to keep our costs in the electricity supply industry. In every way, therefore, we are very greatly indebted to Col. Crompton. Apart from this special work, we must recognize the great work which he has done in standardization and in bringing the nations together in this matter. He has not only been a loyal son of his own country, but has taken a wide international view of the possibilities of electricity, a view from which I am sure we have all benefited. I have spoken of his attainments; I cannot conclude without some reference to the man himself. His amazing energy, his hatred of humbug, his complete forthrightness in all the matters with which he deals, one must admire very greatly. Behind that we have the most delightful and kindly personality, and I feel, as I am sure everyone does who has come in contact with him, how greatly honoured we are to have Col. Crompton as a member of our profession and a Member of our Institution.

Mr. Roger T. Smith: I met Col. Crompton at the first Electrical Exhibition in Paris in 1881, when he was an exhibitor and I a schoolboy. To me, 45 years ago, Col. Crompton seemed very grown up, but ever since that time he has become younger and younger. Perhaps Faraday would be content to know that his Institution Medal should go to a man like Col. Crompton. Of all his multitudinous activities in the electrical industry, probably the one Col. Crompton would like most to connect with this Medal is his interest in the International Electrotechnical Commission. That body was formed in order that electrical machinery and plant made in different countries should be bought and sold on a fair basis, manufacturers and users in five continents agreeing through a method of standardization that things which were called by the same name should really be the same things. Col. Crompton has been recognized throughout these five continents as the father of this Commission. Considering what happens in diplomacy and politics, it is no small achievement that so much agreement in standardization should have resulted from the efforts of the Commission. This agreement is bound by no law and can impose no penalties, but succeeds by the exercise of good will. Col. Crompton has worked, first to create that good will, and secondly to foster it, and I feel sure that the whole of this audience is delighted to offer their hearty congratulations to him on this token of the regard and esteem in which he is held by his brother electrical engineers.

The President then presented, in the name of the Institution, the Faraday Medal to Col. Crompton.

Col. R. E. B. Crompton: It is very difficult for me to reply in any suitable terms to what has been said about me. It is, as applied to me personally, wholly or, at any rate, partially untrue. I have only been one of a band of workers, and, if I have any merit at all,

it has been that I have been like the captain of the cricket eleven—I have chosen good men, and always praised the good men when they did a good thing. The result was progress of a kind which has been useful. In speaking of good men I must speak of one of the best of all—a good woman—that was my wife. When, in those days which Ferranti and I so well remember, we were pushing the idea of electricity supply, we were looked upon as amiable lunatics, or described by the word "cranks," a crank being always a term of opprobrium, and it was very difficult to get the right people to listen to us. My wife, with the splendid instinct of women, had found out who were the people likely to be interested and who were the people likely to help, and she brought them together and succeeded in bringing other people to meet them, so that we had a party of friends who supported us with money and sympathy and, what is more, with a belief in our future, and it was to that band of friends, largely engineered by my wife, that the advance of the electrical supply industry, at all events in London, was chiefly due. So many of them are dead; Spottiswoode, Moulton, Willans, Macfarlane Gray, Lord Kelvin, Rankine, James Thomson—all gone. When I think how much I owe to those great men, and how much I owe to my wife's advice not to proceed solely on my own ideas, but to talk over with others the knotty problems which presented themselves, I feel I have been a very lucky man in taking that advice by which the world has benefited. Something has been said about our international work, and I agree that the last 20 years of this work has been a great pleasure to me. It must be the right thing to get at the best thoughts of other countries as well as of our own, and not be so conceited as to think that we in England are the only people in the world; we have had to find out who were the best people in each country, to bring them together, and get their thoughts. Even so, those who have worked with us will say that we have triumphed, for England is still looked upon as the clear-thinking country where ideas are worked out logically, practically, and usefully, and I think I may correctly say that we are still preserving the position of being the centre of the world of electrical thought. It is very difficult, after the eloquent things that have been said by others, to thank you sufficiently, but I am so deeply touched that I cannot say more.

Lecture on the Telephone.

After the presentation of the Faraday Medal, Sir Oliver Lodge gave a lecture on "The History and Development of the Telephone." (See page 1098).

Mr. J. E. Kingsbury, in proposing a vote of thanks to the lecturer, said :—"In this audience there are those who have followed the development of the telephone over the period referred to by Sir Oliver Lodge, and there are those to whom the subject is in the nature of a novelty, but whether they be experts or whether they take a simple interest in the subject, one and all have found inspiration and instruction from the lecture. It is 50 years since the telephone was invented, and this is its Jubilee, and yet even during this year I have seen many references to other inventors of the telephone, the assumption being that Bell had introduced or improved upon something which had previously existed. Sir Oliver Lodge has made it clear, and I think it is desirable that it should be more widely known, that the telephone was invented by Alexander Graham Bell and that he owed nothing to those who had preceded him or to his contemporaries. He had, of course, the benefit of those researches and investigations in pure science which inevitably lead sooner or later to some practical application for the benefit of mankind. Such information he had in common with his contemporaries, together with some knowledge of the principles of telegraphic transmission. But no contemporary was so equipped as Bell was to comprehend the importance of physical discoveries in acoustics, to realize the methods by which they could be applied for speech transmission, and to apply them. The Institution, and the Council, are to be congratulated on organizing this celebration. Bell's memory ought to be kept green by such commemorations as this. The President, earlier in the day, called attention to Lord Kelvin's appreciation of the telephone. I think Lord Kelvin's prompt and enthusiastic appreciation of the telephone did a great deal to promote its practical development—and however great an invention may be, if it be not practically developed and widely used, it is but a talent buried. The telephone received a stimulus from Lord Kelvin, and I believe that the development and applications of the telephone and its wider use for the benefit of mankind will receive a further stimulus from the lecture of Sir Oliver Lodge. Fifty years hence when in this, or perhaps some other even more imposing building, the Institution celebrates the Centenary of the Telephone, it would not be at all surprising if the lecturer of the period harked back to this day and pointed out how the application of the telephone to the uses of mankind was stimulated by the address of Sir Oliver Lodge."

Prof. J. A. Fleming, in seconding the vote of thanks, said :—"It is perhaps not altogether inappropriate that I should be asked to thank Sir Oliver Lodge for his lecture, because our scientific acquaintance with one another goes back more than 50 years, to a time when we were fellow-students together in the laboratory of Sir Edward Frankland. I was also a fellow-student of Alexander Graham Bell at University College. It is not generally known that the father of the inventor, Mr. Melville Bell, was a lecturer on elocution at University College, London, between 1866 and 1870, and it was there that he developed some of his remarkable work on lip-reading for the deaf. His brilliant son was thus early introduced to the study of phonetics and acoustics. In 1870 Mr. Bell, senior, left England for Canada, taking Alexander with him, and there the beginnings of his great invention were laid. In 1878 Bell came back to London to assist in the establishment of the first telephone company in London and the first early rudimentary exchange. By that time Edison had come into the field with his carbon transmitter and his curious chalk-cylinder receiver, which required to be turned by a handle like a grindstone. The Edison Company was established at 11 Queen Victoria Street, and the Bell Company in Coleman Street. The Bell Company had acquired the rights of the Blake carbon transmitter, and litigation was pending between the

two companies on the subject of the carbon transmitter. The strife was interrupted by the Post Office threatening to attack them both, under the Telegraph Acts of 1868 and 1869, and they had to turn their attention from one another to the Post Office. That celebrated case came on in 1880 and was tried before Mr. Justice Stephen and Baron Pollock—"The Attorney-General *v.* The Edison Telephone Company of London." An army of experts were engaged on both sides, many of whom were Past-Presidents of this Institution, and I think I am the only survivor of that group of experts. That case was settled in favour of the Government, and after that the telephone companies agreed to join together and form the United Telephone Co. It is remarkable how closely the development of the telephone is connected with this Institution. The modern transmitter is more a development of the Hughes microphone than Edison's transmitter, and the Bell receiver remains to-day almost what it was when he conceived it. Therefore the modern telephone system is closely associated with the names of Bell and Hughes. Many present will remember the charming personality of Prof. Hughes, at one time President of this Institution, a great genius and a great inventor. He was born in Great Britain and educated at Edinburgh and received his college education in London, retaining his interest in England to the end of his life. I have much pleasure in seconding the vote of thanks to Sir Oliver Lodge."

The vote of thanks was then carried with acclamation and Sir Oliver Lodge briefly replied.

Annual Conversazione.

At the Annual Conversazione of the Institution held in the evening of the same day at the Science Museum, South Kensington, which was attended by over 1 800 persons, there was shown a very complete exhibit of telephonic apparatus, including specimens of the instrument in all its stages. The exhibit was arranged by engineers of the General Post Office by kind permission of the Engineer-in-Chief, Colonel T. F. Purves, O.B.E.

THE HISTORY AND DEVELOPMENT OF THE TELEPHONE.

By SIR OLIVER LODGE, D.Sc., F.R.S., Honorary Member.

(Lecture delivered before THE INSTITUTION, *24th June,* 1926, *on the occasion of the Jubilee of the Telephone.)*

The majority of mankind deal with material objects, and seldom are concerned with electricity and magnetism, except in the form of completed apparatus designed and constructed for practical use. Their only touch with the ether is through the eye, and that again only tells us about the material objects which have either emitted or scattered the light. Light primarily tells us nothing about itself, nothing about its electromagnetic constitution, and still less about the ether which conveys it.

With matter we are at home, for our bodies are composed of it, while everything about electricity and magnetism has to be inferred from their effects on matter. An electric current can be appreciated as heat, or as the deflection of a galvanometer needle, or as an unpleasant shock. Mankind's first acquaintance with electricity was in the thunderstorm. We only learnt about magnetism because the earth happened to be a magnet. For generations even civilized man knew nothing about these etherial manifestations, and only began to make serious metrical experiments on them in the 19th century. Those phenomena still feel rather aloof from practical life, though it is true that in the 20th century their applications have become numerous. Consequently, when the serious study of electrical phenomena was begun, discoveries were made in a fast and furious manner, and anyone who worked with even simple apparatus of that novel kind might hit upon something new to science.

The articulating telephone is an instrument of absurd simplicity. It was invented by one who was no professed electrician, who was not really learned in physical science, but was interested mainly in introducing precision and clear intelligibility into human speech. Most of us, in talking, slur over words in a careless and incomplete and barely intelligible manner. Clear utterance was never the strong point of the pulpit, though it used to be prevalent on the stage. Even that can hardly be said now: actors are liable to say their parts in a manner which cannot be followed by a foreigner or by the partially deaf: they talk in what is considered a natural way, the way that people talk in ordinary life, a way which is not really admirable.

Graham Bell's own articulation was of the most precise character: his manner of speech was a specially noticeable feature of his lectures, when he came over to England in the year 1877, and excited the admiration of us early members of the Physical Society by his clear enunciation. He had been concerned with the training of the deaf and dumb; he had married, so I understood, a deaf and dumb wife; and had devoted himself to the accurate production of human speech, whether by his own lips and larynx or through its reproduction by instrumental means. He once said, so I am told, that it was fortunate that he was not a scientifically trained physicist; for if he had been he would probably have known (or thought he knew) that an articulating machine of a simple character was an impossibility.

The instruments he had primarily and essentially to deal with, were the human voice at one end and the human ear at the other; and he realized that if one of these was defective the other must be made still more precise and accurate. Thus the telephone arose from a study of articulation. This study he must have inherited from his father, Alexander Melville Bell, the author of a book called "Visible Speech," and other works relating to pronunciation, whose whole life had been employed in teaching people to speak. Clerk Maxwell amusingly said:—

> "He brought the art to such perfection that, though a Scotchman, he taught himself in six months to speak English, and I regret extremely that when I had the opportunity in Edinburgh I did not take lessons from him."

Mr. Melville Bell had made a complete analysis and classification of all the sounds capable of being uttered by the human voice, from the Zulu "clicks" to coughing and sneezing, and had embodied his results in a system of symbols, not alphabetical symbols, but founded on the different configurations of the organs of speech: and a test made by Mr. Alexander J. Ellis, author of "The Essentials of Phonetics," demonstrated the value of Melville Bell's system. His son, inventor of the telephone, was thus prepared by early training in the practical analysis of the elements of speech, and applied his father's system in the Boston School for the Deaf and Dumb; where the results were so successful that, as Clerk Maxwell says, they were not only the most valuable testimonial to his father's system, but an honour which the inventor of the telephone may well consider as the highest he has attained.

Talking machines had been invented before, but they were fearfully complicated—special arrangements for producing vowel sounds (which in our own day have been developed so successfully by Sir Richard Paget); other devices for the explosive noises of consonants; escape of air for sibilants; a toothed wheel for the rolling r's; and so on. By skilled manipulation of a keyboard it was thus possible to make a rough imitation of speech and to utter a few sentences.

Graham Bell's instrument did not aim at thus producing speech *de novo*. It took the sounds emanating from the human voice, and sought to reproduce them at a distance by electrical means; so that at any,

even great, distances, aerial vibrations could be reproduced and interpreted by the human ear, after the same fashion as the original aerial vibrations could be interpreted by an ear close to. The way in which he ultimately found that this could be accomplished was of surpassing and surprising simplicity; and if asked suddenly what was the simplest and greatest invention of the 19th century I should be disposed to say the telephone, for it has not only had its wide effect on extending human intercourse, it has put into the hands of experimenters an instrument of great value. It has revolutionized the detection of minute currents in all manner of sciences; it has made measurements easy which without it would be difficult; in many cases it has superseded the eye as an observing instrument; and now in the present century, supplemented by further discoveries, it bids fair to make wireless telephony possible all over the earth, with international results which can only dimly be foreseen.

It must never be forgotten that the real wonder of this mode of communication between mind and mind lies in the larynx and its associated cavities at the sending end, and in the ear and brain at the receiving end. The thought of an agent A is understood by a percipient P, through a mechanical system of vibration to which we have grown so accustomed that we are liable to forget its marvellous character. By delicate muscular adjustments the air is thrown into vibrations corresponding to the thought in the mind. Those vibrations are received and analysed by the complicated mechanism of the ear; their effects are somewhat mysteriously conveyed by the auditory nerve to the brain, and there are still more mysteriously interpreted by the mind of the percipient; so that if he knows the code called language (and unfortunately mankind has invented far too many of such codes) he can become aware of the thought originally in the mind of the agent or communicator.

Transmission is thus under ordinary circumstances a purely mechanical operation, involving brain-cell, nerve, muscle, vibrating tissue, condensations and rarefactions of the air; then again a vibrating membrane, bones, liquid, nerve endings, with discriminating arrangements for analysing a great range of frequency for notes of different pitch; then nerve again, brain-cell, and so to the perceiving mind, where all this mechanical and physiological disturbance is reinterpreted as thought. The only difference between this ordinary case of conversation, and the modern method of communication across great tracts of space, is that intervening electrical or etherial machinery is employed to effect the transmission over a hundred or a thousand miles of distance in a rapid and almost instantaneous manner. This is done by making the air vibrations either generate or modify an electric current, that is to throw docile and responsive electrons into a corresponding state of motion; the electric impulses being then either broadcast into space, or else guided by a wire to their destination; where, by aid of the magnetic effect of the moving electrons, which again take up the vibrations, an iron plate, itself full of magnetic whirls, is acted on and made to vibrate in a corresponding manner; thus once more producing condensations and rarefactions in the air in contact with that plate; and so ultimately reach the diaphragm of the receiving ear. No sound is transmitted between the two stations, only electric impulses, which travel through the ether with the speed of light, no matter whether they are guided by a wire or not.*

The remarkable novelty in this long-distance transmission method is not so much that the ether is able to pick up and transmit the pulses, by aid of the ingenious mechanism provided: the ether is so docile that it will nearly always do all that is wanted of it, except display and enforce its own existence. The wonder is that a simple iron plate is able thus magnetically to be so affected that it can reproduce and follow accurately, not only the intonations of the human voice, but the sound from every instrument in an orchestra, in a perfect and detailed manner, so that the ideas of Bach and Beethoven in their fulness and entirety can be taken up, at least on the mechanical side, by such a plate, and given to any hearer whose mind is attuned to the reception of the delights of refined musical composition.

This was essentially the surprising discovery of Graham Bell. Crude sounds had been transmitted electrically, before, by Philipp Reis and others. Wheatstone had transmitted the sounds of a musical instrument through a wooden rod to a distant soundboard—an easy and interesting thing to do. But Bell found how to make the vibrations of an iron plate at one end generate fluctuating electric currents which should cause an iron plate at the far end to vibrate in a precisely similar manner, and thus invented the articulating telephone.

Those, now comparatively few, who have lived through the 70's of last century, vividly remember the surprise which the simplicity of the apparatus capable of achieving so far reaching a result aroused when it was first announced. I remember, for instance, the enthusiasm with which Lord Kelvin, after a visit to America, came back to the British Association Meeting in Glasgow, bringing with him a couple of Bell's early instruments, which the inventor had given him, and which he enthusiastically showed to Section A, then meeting in his own lecture theatre, and described his astonishment when he heard a clock-spring actually talk. He had heard it say—a misquotation—" To be or not to be, there's the rub." This early demonstration by Lord Kelvin in this country, under our system of Patent Laws, threatened at one time to have a serious and quite undesired effect in preventing the completion of Bell's patent; a strange anomaly, as I think. But fortunately Lord Kelvin was able to exert his influence; and sensible judicial people found themselves able to evade the technical point and grant the inventor his just right.

The instruments shown by Lord Kelvin were of the simplest character; the sending end and the receiving end were much the same. At one end mechanical

* The speed of light is the ideal speed aimed at but not actually attained on a real line. Even an aerial land line has some troublesome properties, the same as are accentuated in any cable, and greatly accentuated in a submarine cable. Applying Heaviside's complete theory to a well-loaded line, we find that we ought to be able to attain a speed of from 10 000 to 20 000 miles a second; and this speed, Mr. Appleyard assures me, corresponds to what in practice a Pupinised telephone cable actually gives.

vibration generated a current; at the other end that current magnetically reproduced mechanical vibration: that was the whole thing. No energy was put into the circuit, except what the voice put into it, in those early days. Very soon afterwards an Edison carbon transmitter and a Hughes microphone, consisting of granulated carbon in the circuit of a battery, were introduced, so that the voice merely altered the resistance of the carbon granules; the energy came from the battery, and by that means it was possible to magnify the voice, and transmit to a distance any reasonable amount of fluctuating energy. But this microphonic transmitter, still in use at the present day, though it slightly differentiated the apparatus at the sending and receiving ends, did not really complicate matters much: the essential apparatus remained quite simple. There are plenty of complications now; but those complications have to do with the distribution of the messages and the selection of the person talked to. It is obviously no easy matter to enable any one person in the British Isles to communicate with any other by a system of wires; of which each subscriber to the telephone exchange need only have a single pair. A further complication arises when the calling-up is attempted to be done mechanically or automatically, without human intervention, at the central station.

These complications have called for the utmost ingenuity and skill on the part of those engineers who have been engaged in carrying it out. Whenever an invention or a discovery gets into extensive practical use, on the large scale, innumerable difficulties are always encountered, and are nearly always successfully overcome by those who devote their life to the work. To understand these things involves a long apprenticeship, a long period of study with the actual apparatus. For in practical use a device has to be made foolproof, able to be worked by operators with no special skill, and by subscribers who doubtless manage to pick out every weak point and make the thing go wrong if any loophole for misuse is left them. Furthermore, any wide scale application of engineering invention and discovery is open to perturbations of a quite different kind from any which are studied in physics. Operators may strike, peaceful progress may be interrupted by wars of one kind or another; all which complications, if they belong to science at all, belong not to physics or engineering, but, I suppose, to the science of sociology. Human free will is a great asset, but, like everything else of value, it is capable of abuse—sometimes, strangely enough, even when actuated by class-loyalty and other excellent motives.

To return to the early history of the telephone. It was received in this country by some men of science with a certain amount of scepticism, which is only instructive now as showing its novelty. That great chemist, Prof. A. W. Williamson, for instance, was very doubtful whether the messages were really transmitted by electrical means at all; he thought it more probable that the sound actually travelled between the two places by the wire; and he urged me as a young man to look into it and see whether there was not some hocus-pocus in it.

Lord Kelvin, however, as we have seen, received it with enthusiasm, and was able as a mathematical physicist to realize and state the theory of the means by which electrical transmission was really accomplished; though naturally in his lifetime he was not acquainted with the wireless or radio methods now in vogue, made possible by Fleming's introduction of the valve detector, based on a stray observation of Edison's of the unilateral conductivity of electrodes in a vacuum, akin to the unilateral conductivity of a modified coherer or crystal detector.

In 1878 one of the greatest mathematical physicists of the 19th century—possibly one whom posterity will consider, by reason of his far-reaching influence, the greatest of all—viz. James Clerk Maxwell, gave what is called the Rede Lecture before the University of Cambridge, taking "The Telephone" as his subject. And the reasonable attitude of enlightened scientific men in this country to the subject is well illustrated by his opening paragraph, which I will here quote:—

> "When, about two years ago, news came from the other side of the Atlantic that a method had been invented of transmitting, by means of electricity, the articulate sounds of the human voice, so as to be heard hundreds of miles away from the speaker, those of us who had reason to believe that the report had some foundation in fact, began to exercise our imaginations in picturing some triumph of constructive skill—something as far surpassing Sir William Thomson's Siphon Recorder in delicacy and intricacy as that is beyond a common bell-pull. When at last this little instrument arrived, consisting, as it does, of parts, every one of which is familiar to us, and capable of being put together by an amateur, the disappointment arising from its humble appearance was only partially relieved on finding that it was really able to talk." *

Sir Richard Paget tells me that when a talking machine, sent by Graham Bell, arrived for Lord Kelvin in this country he happened to be staying with Lord Winchelsea, who sent a farm wagon to the station to collect it.

I suppose it may be said that the articulating telephone was born on the 10th March, 1876. Up to that time Bell had been working at telegraphic communication, using tuning forks and Morse signals. He was Professor of Vocal Physiology at Boston University. We are told that during his experiments one of the transmitter springs got out of order and made a faint sound in the receiver. He had hoped till then to get the deaf to interpret musical sounds transmitted by what he called "the harmonic telegraph," making a kind of modified and rapid Morse-code system. He thought that if they could not hear, they could see, the signals which were being transmitted, and gradually become able to interpret them; just as they were able to interpret his father's system of visible speech or lip-reading. The accidental observation, however, gave him another clue; and though at first he only got his receiver to make strange and discordant noises, on the 10th March, 1876, his efforts were crowned with success.

* *Nature*, 1878, vol. 18, p. 159.

On this memorable day Bell spoke into an instrument fixed in an attic, to his assistant in the basement, at the other end of 100 feet of wire. All he said was, "Mr. Watson, come here. I want you!" The assistant rushed upstairs into the attic, shouting excitedly, "I heard you; I could hear what you said!" This is the story of the birth of the telephone, as told by Bell himself.

A writer in the *Wireless World* of the 26th May this year goes on to say that, at an Exhibition held in Philadelphia later in 1876, the Emperor of Brazil placed the receiver to his ear and was astonished to hear it speak. Lord Kelvin was there too, and declared, as he listened to the steel spring or diaphragm, which at that time he was told to press against his ear, so as to get the necessary damping—"It does speak! It is the most wonderful thing I have seen in America!"

Now that a telephone is to be found in most households (though not indeed so many in this country as in others, for in America there seems to be a telephone in nearly every room), and now that the younger generation is so accustomed to it that they can hardly imagine a time when it was not in existence, it is well to remember the surprise and delight with which the invention was received. In these days, indeed, it is occasionally customary to regard the telephone as rather a nuisance. I found it so when I was in America in 1920: at any time, day or night, I might be called up by reporters and others. It was very little use to tell the hotel clerk not to switch people on, they got through any ordinary barriers; and, when too much bored, my plan was to turn the receiver on to the transmitter and let the communicator talk back to himself, instead of to me! This usually had the desired effect, and was better than Herbert Spencer's device of stuffing his ears with cotton wool when he was bored by a conversation! The writer in the *Wireless World* says that it is amusing to find that towards the close of his life Graham Bell himself sometimes found the telephone such a source of annoyance that he had it removed from his room. I do not vouch for that; but it seems quite possible, at any rate in certain moods.

Complications.

When we come to consider the developments of the telephone and the complications which naturally inevitably arose during its widespread application, we must go beyond the complications of the telephone exchange, whether automatic or otherwise, and the devices whereby any one subscriber was able to speak to any other; for a more interesting series of difficulties arose in connection with long-distance transmission, especially with international transmission between different countries. So far as England is concerned, that can only be done by submarine cables; and cable signalling is never so easy as free space signals or signalling along land lines. Capacity, in combination with resistance, comes in as a serious consideration, producing distortion and rendering speech through an ordinary cable more than 40 or 50 miles long practically impossible. A cable from Dover to Calais is short enough to be manageable; so that speech from London to Paris is quite good. From Holyhead to Dublin the cable is longer, and speech from London to Dublin must be more difficult. To speak from England to America by an Atlantic cable is impossible, though through the free ether there is no particular difficulty if the power used is sufficient and the receiving instrument sufficiently delicate.

The theory of line or cable transmission, and the mode in which good long-distance telephony has become possible, say over the Continent of America, where long distances really exist, is of high scientific interest, and in any lecture on the telephone must be referred to; but as some of this inevitably involves mathematical treatment, I propose to put in an Appendix a summary or concise exposition of the chief features concerning transmission, whether through land lines, or cables, or through the free ether of space; for the subject naturally divides itself into three portions—the apparatus at the sending end, the apparatus at the receiving end, and the facts and peculiarities about transmission.

But as to the other complications, such as those connected with telephone exchanges, with automatic calling-up, and the elaborate methods necessitated by large-scale telephony and prompt and efficient service, I see here present many who possess real knowledge in these subjects, and who indeed have already communicated information about them. For instance, only last July Colonel Purves gave a valuable paper * on "The Post Office and Automatic Telephones." And I see that in April this year Messrs. Cohen, Aldridge and West read a paper entitled "The Frequency Characteristics of Telephone Systems and Audio-frequency Apparatus." † Mr. Kingsbury's standard treatise on "The Telephone and Telephone Exchanges" is known to all interested in the subject.

I have had offers of help both from Mr. Kingsbury and from your Ex-President, that great telephone authority, Mr. Gill, who is now at Madrid teaching the Spaniards how to develop their system properly. My friend, Mr. Rollo Appleyard, representing him, has put at my disposal any amount of information; but it is impossible to deal with it in one lecture; and, moreover, all this mass of knowledge is best treated by experts with first-hand information. I wish to express gratitude to all those who have so freely offered help, and I regret that I have been unable to make more use of it. I have thought it best to confine myself to the fundamental principles with which my own knowledge is more directly concerned.

I shall not deal with controversial points, nor with the history of previous attempts at electrical conveyance of sound, but shall limit myself strictly to the articulating telephone and its concomitant devices.

By the use of accurate tuning and syntonized circuits it is possible, as everyone knows, to select from a multitude of disturbances in the ether and attend only to the waves of a desired frequency, all others being excluded or tuned out. This process is now worked by a system of carrier waves, where each sending station operates on one definite wave-length, and where the voice at each station merely modifies the amplitude of this wave, with very slight changes of frequency on either side, so as to give the proper fluctuations. This

* *Journal I.E.E.*, 1925, vol. 63, p. 617. † *Ibid.* 1926, vol. 64, p. 1023.

principle, so extensively applied in radio telegraphy, where a number of signals are transmitted through the same ether, can also be applied in line telephony when a number of messages are being sent along the same wire; each speaking only to a suitably tuned receiver. It is also found practicable to use the same wire for telegraphic purposes as well, thus making a composite system. The development of all this elaborate selective method, in practice, involves many technicalities; and I propose to ask Mr. Appleyard to give in an Appendix some indication of the modern practice in that respect. Meanwhile it is interesting to note that this method of composite signalling may be regarded as to some extent a development of the old harmonic telegraph system with tuned reeds, attempted in the early days by Graham Bell before he discovered that it could give voice production. He used tuned reeds where we use high-frequency tuned circuits; but on his plan a number of different tones could be sent by the same wire, and picked out each by its corresponding receiver, the other otherwise-tuned reeds only responding to their own frequencies.

Thus wired and wireless telephony have constantly tended to approximate to one another. Morse signals, as we know well, are transmitted through the ether as well as speech; and though if they are strong they do to some extent interfere, the disturbances are not very prominent and can for the most part be ignored.

Line telephony is, as we know, now much used as a supplement to broadcasting, the transmission from (say) 2LO to a big broadcast station like Daventry being accomplished by line methods, in order there to be imparted freely to the ether. And the sending and receiving devices are not dissimilar in the two cases. Indeed, through a land wire with very little capacity the law of transmission is much the same as in free space. The two are represented by the same equations, as was incidentally pointed out by myself in my paper in the *Philosophical Magazine* of August 1888.* And on the

* *Philosophical Magazine*, 1888, vol. 26, p. 227. A further demonstration of electric waves is reported in the *Philosophical Magazine* for July 1889, pp. 48–65. Heaviside's remarks on the subject will be found in "Communications" to the *Electrician* for 17th August, 1888, p. 479, and 19th October, p. 772; reprinted in vol. ii of "Electrical Papers," p. 486 onwards. And from this volume, p. 489, I make the following extract. He is there upholding the importance of self-induction against the attacks of Sir William Preece. He points out that it is self-induction, or rather electric inertia, which really keeps the waves going; and then he says:—

> "On this question of waves I take the opportunity of referring to a point mentioned at the Bath meeting [of the British Association in 1888] by Prof. FitzGerald [then President of Section A]. That physicist, in directing attention to Hertz's recent experiments, considered that they demonstrated the truth of the propagation of waves in time through the ether; but that, on the other hand, the waves sent along a circuit did not do so, because they might be explained by action at a distance.
>
> "It seems to me, however, that the more closely we look at the matter the less distinction there is between the two cases, and that to an unbiassed mind the experiments of Prof. Lodge, sending waves of short length into a miniature telegraph circuit, with consequent 'resonance' effects, are equally conclusive to those of Hertz on the point named; in one respect, perhaps, more so, because their theory is simpler, and can be more closely followed."

In Heaviside's article on the "Theory of Electric Telegraphy," written for the 10th Edition of the "Encyclopædia Britannica" in 1902, he emphasizes similarity between free and wired transmission, especially if inductance is emphasized and capacity kept small; and gives the whole theory in comparatively simple form. This article is reproduced near the end of vol. ii of his "Electromagnetic Theory," pages 331 *et seq.* He gives in fact "the radiational theory of telegraphy," whether wired or wireless, saying that "it is founded upon Maxwell's theory of light, and had been proved in all essential points and in various details by important experiments of Hughes, Lodge, Hertz, and others." His reference to loaded lines will be found on pp. 344 and 345 of vol. iii of his "Electromagnetic Theory."

In other places he deals with the reflection of waves in wires and cables, the so-called "echo" effects which are often troublesome, and shows how they can be avoided by proper absorbing arrangements at the receiving end.

strength of that fact Mr. Heaviside was accustomed to emphasize the similarity between my observations on wires and Hertz's discovery in free space. We both discovered at about the same time how to generate the waves and detect them. We both measured the wavelength by reflecting the waves and converting them into stationary waves; employing at first sparks or scintillæ, or brush discharge, as the imperfect and inconvenient form of detector; but afterwards using the coherer principle described by me to this Institution in 1890,* and independently rediscovered and improved by Prof. Branly with his smeared metallic powders and assemblage of iron filings. Branly's method of detection enabled the beginning of wireless telegraphy; but the rectifying power of crystals, and especially of the Fleming valve, so greatly improved the power of detection that the transmission of speech and music began to be possible in the first decade of the present century, and has gone on improving ever since.

Advantage of Permanent Magnetism in the Telephone.

In saying that the telephone is simple, it must not be supposed that that simplicity was arrived at straight away, or that the theory of it is unworthy of attention. The instrument consists essentially of a magnet, a coil, and an iron plate. The coil naturally has an iron core, so as to be an electromagnet; but in combining these three things, an electromagnet, a permanent magnet, and an iron plate, many varieties of arrangement are possible; only one of which is really efficient. The inventor's problem was therefore rather like those bridge or chess problems where a certain key move, or a certain discard, is necessary to the solution, and where all others fail.

Even about the iron plate there were many things to ascertain, especially its best thickness or flexibility, and especially the right amount of damping. But the most interesting part of the problem was the need for a permanent magnet. It seemed at first as if an electromagnet ought to do all that was wanted in the receiver, and probably the permanent magnet was introduced in order to enable it to act as a transmitter; for the three things, electricity, magnetism, and motion, are vitally connected. Where two coexist the third follows.

In the transmitter we make use of Faraday's discovery, now nearly a century old—on which manifestly there will have to be a Centenary some time in the coming thirties; for that discovery was nothing less than the birth or rather the conception of the dynamo, the birth, we may say, of electrical engineering, and therefore of this Institution. The discovery, regarded theoretically, was the essential connection between the three things:—in the transmitter magnetism and motion are combined, and the result is an electric current; whereas in the receiver the magnetism of that electric current produces motion. One is a kind of dynamo; the other is a kind of motor.

The transmitter produces alternating currents which synchronize in every detail with the mechanical vibrations of sound, the sound being caused by a regulated blast of air from the lungs through the larynx. In the

* *Journal I.E.E.*, 1890, vol. 19, pp. 352 and 354.

receiver those currents produce corresponding infinitesimal vibrations in an iron plate in front of an electromagnet. The vibrations are of nearly infinitesimal or rather molecular magnitude: they may be quite below the visibility of the eye, but their detection is within the capacity of the ear. Not that the ear is more sensitive than the eye; both instruments are about equally sensitive. The amount of energy which can affect them has been measured by the late Lord Rayleigh and others: he found that the amount of energy is about the same in the two cases. But it must be of the right kind. The ear is sensitive to the motions of matter of a suitable frequency or pitch; and of that kind of disturbance it can detect an amount almost infinitesimally and incredibly small. The eye is sensitive to etherial vibrations, and of those it can detect an amount almost infinitesimally and incredibly small. The one detects infinitesimal motions in the air; the other motions (if they are motions) in the ether. The eye cannot see the vibrations of the iron plate; it is not sensitive to the motions of matter; it can see them only when they are large. The ear does not respond to ether vibrations at all; the eye does. Each instrument has its own field of usefulness, its own function; and in its own field each is supreme.

The telephone makes use of the sensitiveness of the ear, and gives it that with which it is competent to deal. An electromagnet close to a suitably clamped iron plate would seem to be the right detector. An electromagnet is a coil wound on a soft iron core. Why use a permanent magnet at all? Yet it was found essential to employ a permanent magnet to back up the electromagnet. The soft iron core close to the iron plate at one end had to have a permanent magnet at its other end; so that the iron plate should be in a permanent magnetic field. The soft iron core transmitted the lines of force of the permanent magnet, and thus constantly attracted the iron plate. All that the received currents had to do was not to cause that attraction, but to modify it, that is to strengthen or weaken the force of attraction according as the currents were positive or negative.

The theory of that is simple enough but was not at first obvious, and there was some amount of discussion as to why a permanent magnet was necessary. The reason may be put in various ways; it may be expressed geometrically in terms of a curve. Imagine a curve like a hanging chain, and then consider a point oscillating horizontally near the bottom of that curve. The changes in elevation are very slow: an inch of horizontal motion along such a curve corresponds to very little elevation. But if instead of working at the bottom of the curve we work where the curve is steep, then even 1/100th of an inch of horizontal motion would send the point up and down the curve quite a considerable amount. If the slope were 45° the vertical and horizontal motion would be the same; but if the gradient or steepness of the curve were 80° or 89° the vertical motion would be far in excess of the horizontal. Applying that geometrical fact to the special case, we realize that if we were using an electromagnet with soft iron only we should be working at the bottom of the curve; but that if we reinforced it by permanent magnetism we should be working on the steep part of the curve.

But perhaps it is clearer to put the thing algebraically as Heaviside did. The force of attraction depends on the square of the magnetic field. If that field varies between plus and minus h, and if we have to depend on the square of that small quantity, we shall get hardly any result. If, however, we reinforce it by a fixed quantity H, so that we now oscillate between $(H + h)$ and $(H - h)$, and take the difference of those squares, we shall have a very different result. The difference between $(a + b)^2$ and $(a - b)^2$ is $4ab$; and although b may be very small, $4ab$ may be got as big as we please by making a big. Thus the permanent field H comes in as a factor; and what the telephone observes is not the fluctuation in h, but the fluctuation in $4Hh$, which may be of a totally different order of magnitude, depending on the size of H—which is the permanent field supplied in the instrument by the permanent magnet.

In the first instruments the coil was wound over a considerable length of iron core; but it was soon found that the right plan was to use a very short length, to concentrate the coil at the top of the permanent magnet, and to utilize only the fluctuations in a strong permanent field; thus working on the steep part of the curve, and making the permanent magnet contribute to the sensitiveness by supplying a constant factor to the periodic or fluctuating disturbances which had to be observed.

Whether a double-pole or horseshoe magnet was used, or whether a steel bar magnet was employed, is a mere detail of construction and convenience. The essential thing was the need for permanent magnetism in the receiver.

This mode of regarding the influence of a permanent magnet in the receiving telephone is, however, incomplete; for it would suggest that the stronger the magnet the better, and that if greater sensitiveness were required it could be obtained by the use of a strong electromagnet instead of a steel one. But if that were tried it would be found to defeat its own end. The soft iron inside the coil must not be saturated with magnetism; for then its magnetism would not fluctuate: the currents in the coil would have no effect upon it. The permeability of iron is rather a delicate matter—for reasons which Sir Alfred Ewing was able to demonstrate by his flock of compass needles. It is known that the act of magnetization is the turning round and facing in one direction of a large number of pre-existing magnets or magnetized molecules, and that there are three stages in this operation in most kinds of iron:—

> First, when the applied force is too small to disturb them in any large number;
>
> Second, when they begin to topple over, or turn round, in an almost unstable condition under their mutual forces; and
>
> Third, when the majority of them have already faced round; so that a further force has little or no effect.

That third stage is saturation, and in the telephone must be avoided. The application of a permanent

magnet of moderate strength brings the iron into the intermediate or sensitive stage, when its permeability is very high. If the applied magnet is too weak the iron remains in the first stage, with low permeability. If the applied magnet is too strong it gets into the final stage, which is also of low permeability. The intermediate stage is the one to aim at when sensitiveness is required.

Hence there is a best strength of permanent magnet, which presumably is hit upon by the experience of instrument makers. The magnet may be too weak, but it may also be too strong. In other words, though it is true to say that the result depends on the product of H and h, we must also remember that h is not independent of H. Its value depends not only on the received currents, but on the condition of the iron core, and if H is too strong, variations in h will be zero.

So much for the receiving instrument. As for the transmitter, similar considerations will apply to that if Bell's original magnetic transmitter were used; but as it has been entirely superseded by the microphone, which depends on the fluctuations of resistance in the contacts of carbon granules in circuit with the battery, there is nothing much to be said about that, except that it is undesirable to send the battery current itself into the line and through the receiving instrument. It is better to employ a transformer, for that transmits no steady current at all, but only the currents induced by the variation in the primary current. The line thus receives nothing but alternating currents, which are able to do all that is wanted without exerting any polarizing or steady perturbing effect on the receiver; the strength of the induced currents being proportional, not to the strength of the primary current, but to its rate of variation.

Transmission.

We have now to consider the transmission of these alternating currents along the wire or cable or whatever is used to connect the sending and receiving stations. Any perfectly insulated transmitting line possesses three definite characteristics, which are independent of each other, none of which can be entirely obliterated, but any one of which might be reduced to a comparatively small amount. These three are resistance, inductance, and capacity.

A land line has small capacity; whereas in a submarine or buried cable capacity is emphasized. Every line unfortunately has resistance; and resistance is wholly obstructive to transmission: it does not help it in the least; it dissipates energy and converts it into heat. Resistance is therefore a necessary evil. The only way to reduce the resistance of a metallic conductor to zero is to cool it within a few degrees of the absolute zero of temperature. This can be done in the laboratory by means of liquid helium—as was done with astonishing results by Kammerlingh Onnes. But in practice no such device is ever likely to be feasible: if it were, signalling by such wire to any distance would be very easy.

The effect of resistance alone is attenuation of the signals, their energy being gradually absorbed and consumed in warming the wire. There is another cause of attenuation, viz. leakage. If the wire is not perfectly insulated, part of the current does not reach its destination; it leaks out through the imperfect insulation, and returns to its source without having gone the whole way. Leakage, therefore, would cause attenuation even if there were no resistance; but, by the use of good insulation, leakage can be diminished to such an extent that its effect may be almost negligible, and hence the leakance characteristic of a wire is not usually mentioned along with the other three.

Capacity differs from leak, though it too is a lateral effect, inasmuch as it wastes no energy; it stores the energy in an elastic manner, and therefore by itself does not cause attenuation. It does not stop transmission; it only retards it, making the process slower than it otherwise would be—somewhat as if we rang an ordinary bell by an elastic cord instead of by a rigid bell wire. The pulse would reach the distant end in time, though it would arrive smoothed out and slowly, instead of as a definite jerk—just as elastic springs are used in a road vehicle to smooth out the shocks of the road, and deliver them in a gentle and indefinite and inoffensive manner.

The deleterious effect of resistance and capacity in combination is "distortion," which means the obliteration of features and the transmission of pulses of different frequency at different rates: so that if a note and its harmonics were being transmitted as a complicated curve, that curve would not arrive in the same shape as it was sent. The different harmonics would travel at different rates, and accordingly the features of the curve would be unrecognizable; the shape of the curve would be altered or distorted, and the definiteness required for clear signalling would be unattainable.

This was the main difficulty which the early telegraphists were up against, when they began to construct and utilize long cables; and Lord Kelvin gave the theory of cable signalling, taking into full account the combined effect of resistance and capacity, devising what was called the "*KR*" law, familiar to all the older telegraphists, especially to the Society of Telegraph Engineers, which preceded the establishment of this Institution. Probably it is now often called "*CR*." Kelvin, then Professor William Thomson of Glasgow, worked out this diffusion theory of cable signalling in the later fifties of last century, and showed that the law of transmission was exactly analogous to the transmission of heat. He showed that it was a process of diffusion, analogous to the diffusion of salt or sugar or any other substance in water, or the diffusion of smells through air. No definite velocity could be assigned; the rate of transmission depended only on the sensitiveness of the receiving instrument. If a bottle of ammonia were opened on this platform a dog at the back of the hall might smell it at once; but the people would not smell it for some time, though after a time everybody in the hall would smell it, though a person with a cold might be a long time before he perceived it.

Another analogy is furnished by an imaginary attempt to signal by means of fluctuations of temperature at the far end of a long rod swathed in cotton wool, to the near end of which alternate flame and ice

are discriminatively applied. The quickness of response by a thermometer at the far end of the rod would depend entirely upon how sensitive that thermometer was. If it could only feel, say, the tenth of a degree rise or fall, signalling would be very slow; but if it could feel a millionth of a degree, or less, there need be but little delay in receiving the signals. For the heat pulses have no definite velocity, they begin to diffuse at once, and by a sufficient (perhaps impossibly) sensitive instrument could be detected almost immediately.

It was on this theory that Lord Kelvin knew that the solution of cable signalling was to be found in receiving instruments of surpassing delicacy: that is how he came to invent first his mirror galvanometer, and next his siphon recorder—instruments which were able to detect, like the dog's nose or the hyper-sensitive thermometer, the very first beginnings of the transmission. Each pulse sent was therefore to be extremely feeble and to be curbed by an opposite pulse as soon as possible, so as to be ready for the next pulse, without allowing time for any accumulation, such as would be needed to affect a coarser instrument.

But although this served well enough, and is still in use for telegraphy, distortion is only thereby minimized; it is not avoided; and even a small amount of distortion is destructive as regards telephonic transmission. Speech through a long submarine cable is impossible. The combination of resistance and capacity might allow it through a cable 50 miles long, but not more. For the distance to which an alternating current of frequency n can be received without too much attenuation is inversely proportional to $\sqrt{(nCR)}$. The higher frequencies, on which the characteristics of speech depend, are therefore rapidly blotted out. The fundamental note might be received, but the harmonics would be wiped out; and nothing would be got but a featureless and unintelligible drone.

The amplitude is reduced to $1/e$th of its value, or the energy to $1/7$th, in a length

$$\sqrt{\left(\frac{1}{\pi n C_1 R_1}\right)}$$

which may be called the damping distance.

It will be observed that this distortion is due to the inclusion of n, the frequency, along with the CR. If any one of the three factors could be kept small then the transmission might be clear and definite. We cannot keep n small in telephony; for the high harmonics are necessary. We cannot make R small, except by the use of an unwieldy amount of copper or by the impracticable device of excessive cooling; but we have some control over C. Instead of surrounding the copper wire with gutta-percha and a metallic sheath, such as is needed in submarine cables, we may surround the wire by air, supporting the wire by paper; and these air-spaced cables are in actual use for telephonic purposes. Even if we support the wires on poles a good distance above the ground, capacity effects are only minimized; they cannot be wholly avoided. Is there any way of avoiding distortion altogether?

This problem was attacked by that remarkable mathematician Oliver Heaviside, who took into consideration a factor neglected by Lord Kelvin, viz. inductance; or rather inductance and leakance in combination; and showed for the first time how to produce a distortionless cable. Heaviside's theory was not well received by practical electricians. It seemed to them quite natural that the two factors which he introduced must be harmful, not helpful. Leakage (which, when measured in mhos, like conductance, he called "leakance") seemed clearly a thing to avoid; for it could only result in attenuation; while inductance seemed merely to add to impedance; it seemed likely only to obstruct the signals, not in any way to help them. Consequently it was some time before his theory received practical application.

It was taken up to some extent or advocated in this country by Silvanus Thompson; and somehow the genius of Pupin in America enabled him to perceive that inductance would be a help. The addition of inductance is equivalent to an increase of inertia; and Pupin was able to persuade American financiers to risk the construction of loaded cables. It was true that inductance increased impedance; but that by itself turned out not to be deleterious. What was wanted in order to avoid distortion was to get all frequencies to travel at the same rate, so as to preserve the features. A massive disturbance with plenty of inertia behind it could overcome the elastic effect of capacity, and enable the signals to arrive in much the same condition as they started.

Heaviside had shown that when the factor of inductance was introduced, the law of transmission was entirely modified, that there was some approach to a true wave propagation with a definite velocity, and that the head or front of the signal would reach its destination with some approach to the velocity of light. There might then be more attenuation; but attenuation alone was not the evil. It was the discriminative attenuation that was bad. Mere attenuation would not prevent telephony, if only distortion could be avoided. If all frequencies could travel at the same rate, it did not so much matter what that rate was. The addition of inductance makes some approach to this condition; and accordingly many loaded cables are now in use: some of them with extra inductance coils arranged at regular intervals; but some with the copper conductor surrounded by iron tape or wire whipping, thus adding to the inertia of the current, and enabling it to reach its destination sufficiently unimpaired even for telephonic purposes.

Outline of Transmission Theory.

Denoting the resistance per unit length by R
the capacity or permittance by C
the inductance by L
and the leakance by G

the distortionless condition is that

$$CR = GL$$

The velocity of waves through the cable is then

$$\frac{1}{\sqrt{(CL)}}$$

which is independent of the frequency n.

In the general case the cable theory equations are two:—First, the Ohm-law or current equation,

$$RI = -\frac{dV}{dx} - L\frac{dI}{dt}$$

Second, the capacity or potential equation:—

$$C\frac{dV}{dt} = -\frac{dI}{dx} - GV$$

(See Appendix II.)

The first two terms in each of these equations constituted Lord Kelvin's theory, which ignored L and G, and they are analogous to those for diffusion of heat through a slab. Heaviside's completion of the theory consisted in adding the third term to each equation, and thereby laying down a law which, being much more complete and satisfactory, has proved intensely useful in practice.

The leakance or G term can occur in heat also, when the flow of heat is along a rod instead of a slab, but there is nothing in heat to correspond with the inductance L. That is a sort of inertia term characteristic of matter, and likewise of electricity. It is that term which gives to electrical waves their definite velocity, and it is practical emphasis on and exaggeration of that term which has so greatly improved telephonic transmission. We now know that this factor L confers a definite velocity upon electric waves, even in a cable—at least upon the initial pulse or head of a series. The rest of the series cannot live up to it, they draggle along in a diffusive manner in an ordinary cable; but the first pulse or head travels clearly and definitely; it does not reach the distant end instantaneously, it gets there, in the ideal case, with the velocity of light. The subsequent series of waves shuffle along as best they can, unless the cable is distortionless. In that special case they manage to shed their troublesome portions, with inevitable attenuation, leaving a fine naked residue to travel as a free unhampered true wave, feeble but effective up to the limit of its strength.

I am not aware that a really and fully distortionless cable, constructed in accordance with Heaviside's theory, has ever been made, nor do I know if it is practicable; but every approximation to it helps. He showed that the right condition was to apportion the four characteristics, resistance, inductance, capacity and leakance, in such a way that the ratio $R:L$ was equal to the ratio $C:G$, G being the leakance. In that case the velocity of transmission would be quite independent of the frequency; so that all the harmonics would arrive together and every feature would be preserved. The attenuation would undoubtedly be great; but as there was no distortion, considerable power might be applied; or on the other hand, since the signals would be received in unimpaired condition, however weak, they could be magnified up to any desired extent.

Whether such a cable will ever be constructed I do not know; it seems probable that modern discoveries have rendered it unnecessary. Fleming's invention of the valve detector has put into our hands an automatic relay of surpassing docility; further improved by Lee de Forest; and long-line transmission can now be attained by a succession of short lengths of cable or land line, connected together by valve relays; so that the currents from the sending station are not sent very far before they are relayed on, with fresh energy, by a valve transmitter, and started afresh on their new journey. The American Telephone and Telegraph Co. have in this way, so I understand, effected admirable speech transmission across that Continent.

Is there any other way of avoiding distortion? There certainly is if we are content to eliminate the transmitting line altogether, and instead of directing the signal to a desired destination, to broadcast it through the free ether of space; for the ether has properties far more perfect than any form of matter. None of the difficulties of metallic conduction apply to that. It is entirely devoid of resistance—by which I by no means mean that it is a perfect conductor; it is not a conductor at all. It has no resistance because its resistance is infinite. It does not act by conduction. Neither has it any leakage. It acts simply and solely by inductance and capacity. It transmits true waves, all at the same definite speed, no matter what the wave-length or frequency may be. Accordingly it transmits without a trace of distortion. Whatever disturbances are imparted to the ether travel unchanged and arrive unchanged. There is not even any real attenuation. Of course the waves spread out by reason of distance; but the same amount of energy passes through any spherical envelope, however large. The ether is absolutely transparent.

Whether the interstellar spaces contain particles of matter, stray electrons, and other particles of dust, may be argued. But that for all practical purposes the interstellar spaces are absolutely transparent, is certain; else we should not see the distant stars, some of which are 30 thousand light-years away. Indeed it has been estimated that there are some spiral nebulæ as much as a million light-years away; and yet they can be photographed in a large telescope! And the message they convey as to their atomic composition can be accurately deciphered!

Thus in free space there is no attenuation and no distortion. Signals transmitted by free ether, whether they be those of light, or of longer ether waves carrying with them the peculiarities of speech or music, can be detected at any distance—weakened by the spreading out, but otherwise unimpaired. And by suitable magnifying devices the conserved peculiarities can be magnified up and can reproduce the speech and music in any part of the earth. This shows how little mere attenuation matters, so long as distortion is avoided. If the features are there, even though they are infinitesimal, they can be magnified, if necessary a millionfold, till they become perceptible. The theory of wave transmission in the ether is the simplest possible: there are no complications, such as the presence of matter necessarily introduces.

All the complications introduced into wireless or radio telephony belong to the atmosphere. Some of them are hurtful, but some are strangely helpful. The Heaviside layer of free ions and electrons has been shown both by Dr. Eccles and by Sir Joseph Larmor

to have the effect of curving the waves round the earth in a surprising and unexpected manner; thus tending to preserve them in the earth's neighbourhood, where they are useful, and prevent their spreading out too lavishly into the depths of space. Nevertheless, into the depths of space some of them must go; and though they would be violently attenuated by the time they reach the planet Mars, I see no reason why one of our skilled amateur observers, if he could take his instruments with him to that planet, should not be able to detect them and interpret them. Whether the inhabitants of Mars (if there are any) have the skill to detect them I do not know; and whether they could interpret them if they did is more than doubtful. The ether conveys to us a large amount of information about the other worlds in space; but it conveys it not by human artifice or code, but by means of the waves of light which humanity has somehow learnt not only to receive but also to interpret. The interpretive powers of the mind seem nearly unlimited. We are a part of the universe, and the universe seems gradually apprehensible by us. Many things are still mysterious, but nothing seems likely to be ultimately and deeply unintelligible. The progress of science is based upon faith in the ultimate intelligibility of everything; and so far wisdom has been justified of her children.

APPENDIX I.

The Tones of an Iron Plate.

A telephone plate is a flexible disc of iron clamped at the edges. The modes of natural vibration possible to such a plate were calculated by the late Lord Rayleigh,* with his usual comprehensive power, and shown to require for their solution certain Bessel functions whose values have been calculated by my brother, Alfred Lodge.

A simplified expression for the natural frequency of a plate of radius a and thickness z is :—

$$n = \frac{2 \cdot 5\, z}{\pi a^2}\sqrt{\left(\frac{Y}{3\rho(1-\mu^2)}\right)}$$

where Y is the Young's modulus of elasticity, ρ the density, and μ the Poisson ratio, of the material of which the plate is made.

It appears from this that an iron plate of, say, 4·4 cm diameter, and thickness 0·2 mm, has a fundamental frequency of vibration about 990 per second. The first harmonic comes out about two octaves higher. But a telephone plate is well known to respond to all manner of frequencies, much lower as well as far higher than these natural tones, consequently resonance must play but a small part in the reception of vibrations by such a plate; it must be damped so as to be actuated only by forced vibrations, and must respond to almost any frequency whatever. The astonishing thing is the perfection with which it does so respond. That fact alone may be regarded as a practical discovery of Graham Bell's. Precision of utterance by a damped plate was not expected, and the fact took the scientific world by surprise.

Such a plate is also very effective as an auxiliary to the ear. The amplitude of vibration needed for audibility when a plate is held close to the ear is exceedingly minute, comparable indeed with 1 ångström, or the atomic dimension of 10^{-8} cm. The minimum amplitude necessary for audition was measured by Lord Rayleigh as less than 8×10^{-8},* and was estimated as perhaps as low as 10^{-8}. The current needed to produce such amplitudes was also measured, and found to be of the order 10^{-8} ampere, at least for the pitch to which the ear was most sensitive, i.e. for a rate of vibration between 500 and 1 000 per second. Much lower figures for minimum currents have been obtained by Prof. Tait and others.

The telephone used by Lord Rayleigh for this determination was a unipolar Bell telephone of 70 ohms resistance; but he points out that—

> "the effect of a given current depends, of course, upon the manner in which the telephone is wound. If the same space be occupied by copper [of given quality] in the various cases, the current capable of producing a particular effect is inversely as the square root of the resistance."

Hence with a high-resistance telephone it is not surprising that currents as low as 10^{-12} ampere, or the millionth of a microampere, have been found to yield a faintly audible result, especially if the note happened, or was arranged, to correspond to one of the natural harmonics of the plate, so as to be reinforced to some extent by resonance.

APPENDIX II.

Transmission Theory.

The theory of the cable is to determine, on fundamental principles, what sort of current is produced at one end, when either a sudden or an alternating E.M.F. is applied at the other. For that purpose we write down the relation between current I and potential V at every point; and if we take nothing but resistance R and capacity C into account, we have first to express Ohm's law, namely that the current in any element is the difference of potential between its ends divided by its resistance: in other words that RI equals the gradient of potential, if R is the resistance of the wire per unit length. So our first equation is :—

$$RI = -\frac{dV}{dx}$$

Next we have to say that the accumulation of charge at any point per second dQ/dt or $Cdx \,.\, dV/dt$ (C being the capacity per unit length) must correspond to the defect of current that flows away from that element compared with that which arrives; that is to say $-dI$; or in other words that C times the rate of

* See Rayleigh's "Sound," vol. 1, § 221*a*.

* *Proceedings of the Royal Society*, 1877, vol. 26, p. 248.

change of potential must equal what may be called the gradient of current.

$$C\frac{dV}{dt} = -\frac{dI}{dx}$$

Those two equations contain the essentials of the theory, and only need solving by the devices of pure mathematics. The simplest solution is when the applied disturbance is sinuous, with a frequency $p/(2\pi)$; and Fourier taught us that any disturbance may be analysed into a selected series of such harmonic or sinuous components, with their frequencies proceeding in regular order, 1, 2, 3, etc. But first the two equations —the one which expresses what happens longitudinally along the core of the cable, where resistance is dominant, and the one which expresses what happens laterally, or in the insulator surrounding the cable, where capacity is dominant—can be combined into one, so as to eliminate either I or V and to retain the other. This simple process gives us the equation for either I or V in the form :—

$$\frac{d^2I}{dx^2} = CR\frac{dI}{dt}$$

which is the recognized diffusion equation, or equation for the conduction of heat; the solution of which for the case of an applied sinuous variation of frequency $p/(2\pi)$ is :—

$$I = I_0e^{-kx}\cos(pt - kx)$$

where k is an abbreviation for the controlling constant

$$\sqrt{(\tfrac{1}{2}pCR)}$$

This equation represents waves of diminishing amplitude, and shows that the amplitude of these waves will be reduced to $1/e$th of its value in a length $1/k$ or $\sqrt{(2/pCR)}$. Hence the energy, which depends on the square of the amplitude, will be reduced to 1/50th of its value in the length $2/k$; and to the 1/2 500th part in double that length. The high frequencies are therefore wiped out very rapidly, even though CR is kept as small as possible, and the features of a complicated disturbance—which depend on high harmonics—are lost.

The bracketed or cosine part of the equation represents waves of a kind, advancing with the velocity p/k or $\sqrt{(2p/CR)}$, and therefore with a velocity which differs for every frequency; as if the treble notes of a distant band were heard first and then the bass notes—rendering music from it impossible.

Heaviside's Generalized Theory.

Such was the theory on which Atlantic cables were constructed and laid in 1865 and 1866. It ignores both leakage and inductance, since these are supposed to be, and in ordinary cases are, small. But Heaviside's complete theory took them into account. Call the leakance per unit length G, and the inductance L; then the two equations with which we started become :—

First, $$RI = -\frac{dV}{dx} - L\frac{dI}{dt}$$

for the gradient of potential is supplemented or interfered with by a self-induced opposition E.M.F. proportional to the rate of increase of current strength;

and second, $$C\frac{dV}{dt} = -\frac{dI}{dx} - GV$$

for the accumulation of charge at each point is diminished by the leakage, which will be proportional to the potential there.

Combining these two equations into one, so as to retain one of the variables V or I and eliminate the other, is in the general case rather complicated; but the sinuous case is easily represented by the dodge of expressing a sinuous disturbance as e^{ipt}. For e^x is well known to be its own differential; and so

$$\frac{d}{dt}e^{ipt} = ipe^{ipt}$$

Moreover, as Euler showed long ago,

$$e^{ix} = \cos x + i\sin x$$

so that both its real and imaginary parts, which are easily kept separate, are of sinuous character.

The single equation, in the simply harmonic or sinuous case, can therefore be written (whether for I or V) thus :—

$$\frac{d^2V}{dx^2} = (R + ipL)(G + ipC)V$$

There is one very simple and definite relation which might hold among the constants of such a cable, namely when $CR = GL$; and then the old bugbear CR can be neutralized by a combination of the previously neglected quantities G and L. There will now be inevitable and even great attenuation, but there will be but little distortion; none at all if the specified condition is exactly fulfilled. Only we observe that the two things which had hitherto been neglected—because in practice they could be kept small—namely leakance and inductance, have now to be increased artificially, so that their product shall equal the product of the inevitable and deleterious quantities C and R.

If that is so adjusted, the attenuation constant or logarithmic decrement of amplitude will be :—

$$q = \frac{R}{L} = \frac{G}{C}$$

so if we allow for this, and take U instead of V, such that $V = e^{-qt}U$, the above equation can be got into the form :—

$$\frac{d^2U}{dx^2} = LC\frac{d^2U}{dt^2}$$

which shows an undamped quantity U, travelling along x, as a true wave, with a velocity independent of frequency, and equal to $1/\sqrt{(LC)}$.

The actual wave is the same, only damped or violently attenuated in accordance with e^{-qt} or $e^{-Rx\sqrt{(C/L)}}$. We might therefore write the current or the potential in such a distortionless cable at any point x and at any time t as proportional to :—

$$V = e^{-(R/L)t}f\left(x - \frac{t}{\sqrt{(LC)}}\right)$$

if $f(x)$ represents the initial value of V. While the current is :—

$$I = V\sqrt{\frac{C}{L}}$$

This equation represents true damped waves, all travelling at the same speed. But for this to hold it is essential that R/L shall equal G/C, which is not a condition easy to fulfil. It is usually only approached: and, in considering the approach, we note that leakage contributes greatly to attenuation, while inductance does not. In fact, inductance usually diminishes the attenuation constant; hence of the two factors G and L, whose product aims at being equal to the product CR, L is the factor to encourage. Loaded cables therefore aim at some not very close approximation to the distortionless case; and they do this by increasing L to every practicable extent, and by allowing such amount of G as shall not attenuate the signals too much. The signals are clarified, though weakened, by an increase of G.

Wireless operators are familiar with the extra clarity of weakened signals when distortion is avoided. Their kind of distortion is not produced by the complication of cable theory, for they are transmitting through free ether; their kind of distortion is caused by the extra complication of mutual induction between coils, i.e. by the reactions between different parts of their receiving circuit, or by overpressing of valves, so as to get more out of their set than it is entitled to give.

Transmission through Space.

As soon as we abandon guiding lines or wires, and trust to transmission broadcast across space, i.e. as soon as we abandon matter, and entrust our messages to free ether, we get rid at a stroke of a multitude of transmission difficulties—caused some of them by selective dissipation of energy, and some by different waves going at different speeds. The only distortion we now experience is instrumental distortion. In radio transmission there is no other kind; the ether dissipates no energy and generates no heat, except in regions where traces of matter are present. The waves spread out with distance, and therefore we get dilution, but no proper attenuation; all the energy is transmitted without loss, though over a gradually increasing area. And so, even at a distant place some energy is there, unimpaired in quality, ready to be picked up by a collector, and able to be magnified to any desired extent.

The damping constant, which in cables and land lines is $\sqrt{(\frac{1}{2}pCR)}$, is zero in free space, because the factor R is zero. Nor is there any leakage; the term ceases to have meaning. The only controlling constants are C and L, the elastic term and the inertia term, and they are reduced to their essentials. The capacity per unit length of wire is dependent on its diameter and surrounding material and on its distance from earthed surfaces. The inductance depends also on the wire's dimensions and on the medium surrounding it; in each case these quantities have a geometrical factor dependent on the shape and arrangement of matter, and also an essential factor dependent on the unknown but utilized properties of the ether. A capacity is usually an area divided by a thickness (or what is essentially a length, expressible in centimetres) multiplied by the specific inductive capacity of the surrounding medium, commonly called k. An inductance depends on the dimensions of wire, sometimes multiplied by the square of a number of turns, and also multiplied by the magnetic permeability of the surrounding medium, commonly denoted by μ.

In free space none of the geometrical dimensions appear; they have no significance; nothing but the two constants k and μ remain; and the velocity of wave transmission is given no longer by the product CL, as in the distortionless cable case, but by their rudimentary essentials or residues $k\mu$. In fact the velocity of waves in space, instead of being $1/\sqrt{(CL)}$, is simply $1/\sqrt{(\mu k)}$. Such velocity is quite independent of frequency or wave-length; all waves travel at the same pace.

Moreover, instead of the attenuation factor $e^{-\sqrt{(\frac{1}{2}pcR)}}$, we have simply unity, for the index is zero.

The whole transmission is effected by the elasticity and inertia-like properties of the ether, and the two fundamental equations would become :—

$$\frac{dV}{dx} + \mu\frac{dI}{dt} = 0$$

$$\frac{dI}{dx} + k\frac{dV}{dt} = 0$$

if we were entitled to write them like the wire equations, and ignore, rather absurdly, the three dimensions of space.

The true equations must be expressed in terms of magnetic field H and electric field E, and may be briefly written :—*

$$\text{curl } H = k\dot{E}$$

and $$\text{curl } E = \mu\dot{H}$$

These equations represent the essential interaction of those two fields, and exhibit the production of waves when they coincide at right angles and agree in phase. For, using the imperfect one-dimensional equations above, and combining them into one as before so as to eliminate I, we get for the propagation of potential (or of displacement currents if we eliminate V) :—

$$\frac{d^2V}{dx^2} = \mu k\frac{d^2V}{dt^2}$$

an equation well-known to represent true waves advancing with a definite and uniform speed $1/\sqrt{(\mu k)}$. These are what wireless aerials pick up, and turn their elastic displacement currents into conduction currents; such currents of course dissipate energy, but, nevertheless, they operate on the valve or other detector, either through a transformer or by direct tapping, or else they start a syntonized circuit oscillating.

* See for further explanation, if necessary, my Address to the Physical Society on "Opacity," in February 1899, *Proceedings of the Physical Society of London*, 1899, vol. 16, p. 343; or *Philosophical Magazine*, 1899, ser. 5, vol. 47, p. 407.

APPENDIX III.

NOTES ON PRACTICAL DETAILS.

By ROLLO APPLEYARD, O.B.E., J.P., Member.

In response to the request of Sir Oliver Lodge, these few notes have been put together to indicate in broad outline some of the features of telephone development. The written history is contained in innumerable technical books and papers throughout the countries of the world. To those of us, however, who, like Sir Oliver Lodge, can recall the early and subsequent triumphs of telephone engineers as exemplified by results, there is an unwritten history, even more concise and impressive, in the universal telephone-network itself, with its associated apparatus that listens and speaks so faithfully to humanity that humanity forgets the mechanism and thinks the power its own. Twenty years ago Lord Kelvin invited those who desired to learn the story of telephony, to look around. To-day, his words may be repeated as an appropriate tribute to Graham Bell. *Si monumentum requiris, circumspice.*

EXCHANGE AND SUBSCRIBERS' EQUIPMENT.

The earliest form of equipment for interconnecting subscribers followed closely that used in telegraphy, i.e. either a dial type or a peg type of switch. The calling was effected by a separate electric-bell circuit. As the number of subscribers increased, this system became too slow and too cumbersome. The standard switchboard, with spring jack and cords, was next evolved; it was more compact and more easily operated than the preceding arrangement. A battery for the calling and the speaking circuits was at first retained. With increase of distance, however, magneto calling and clearing, with drop-indicators, was introduced; but as the number of telephone users increased, the interconnections between the various standard switchboards involved complicated methods of operation with consequent delay.

The next advance was the magneto multiple-board, in which each operator at an exchange, besides having a certain assigned group of subscribers to attend to, had within reach, for interconnecting purposes, a jack field enabling each operator to connect with any subscriber in the exchange.

As this jack field involved line contacts at each jack, i.e. as each line passed through the contacts of its corresponding jack in series in each multiple field, there was trouble from dust and other causes. To overcome this, the jack connections were branched from the lines, i.e. they were put in parallel. At the same time, was also introduced the self-restoring indicator. At this stage each subscriber's apparatus comprised a receiver, a microphone, an induction coil, primary cells for speech current, a magneto-generator for the calling and clearing currents, and a switch-hook for making circuit changes.

It was realized that great saving could be brought about by transferring as much equipment as possible from the subscribers' stations to a central point, i.e. to the exchange. In accordance with this principle, the common-battery system was developed. The common-battery subscribers' set consisted only of a receiver, a microphone, an induction coil, and a switch-hook. This system had the additional merits of: (1) Centralized maintenance, because the whole battery-supply for calling, talking, and clearing is centralized at the exchange, where it is under constant care and supervision. (2) Lamp-signalling, which is more positive and effective than the drop-indicator. Moreover, with the common-battery system, transmission over the connecting cords, i.e. over the cord circuits, is much more efficient than with the preceding systems. The common-battery system is still in use throughout the world; but in districts where labour-charges and space-costs are high it is being superseded by automatics or machine-switching.

The machine-switching system, though it embodies the transmission features of the common-battery system, eliminates the human element for operation purposes, except for special services. Automatic systems employ either step-by-step or machine-driven switches. In automatic systems the subscriber's apparatus is similar to that of the common-battery system, with the addition of an impulse sender, i.e. a dial-switch. In the step-by-step system the various automatic switches that enter into a connection are actuated directly by the impulses sent from the subscriber's dial. In a power-driven system the switches are actuated by gears or clutches worked from a continuously rotated shaft; the switches are controlled, however, by a group of apparatus known as a register, which receives the current impulses from a subscriber's dial, stores them, and at the appropriate moment controls the switch movement in conformity with the setting of the register. The step-by-step system has been further developed by the introduction of the director which acts in a similar way to the register of a power-driven system, i.e. it receives the impulses from a subscriber's dial and later sends out the impulses necessary to operate the step-by-step switches.

GROWTH AND DISTANCE.

As soon as the principles and methods of transmission began to be understood, they were applied with the object of ensuring a service specified to be not inferior to a prescribed standard of "commercial speech" between any two users. For accomplishing this, several alternatives present themselves, and in any particular case it is necessary to take economic factors into account. The forecast of telephonic growth over a given period, and similar calculations, are usually comprised in a development study. Under present circumstances, preparation has to be made for future increase in the number of channels of telephonic communication, and for differences in the number and character of demands upon lines and equipment. These particulars govern such requirements as the number of operators, the number of switchboard positions, the scope of switchboards, operators' loads, and the design of line plant.

The relationship between traffic and conditions of operation depends upon certain numerical factors such as the average duration of a call, the number of subscribers allocated to each answering operator, the number

of calling switchboard positions, and the number of junctions and groups of junctions between exchanges. From this and similar data can be settled the best route for telephone traffic throughout the system.

At the time of the introduction of telephony on a commercial scale, it was the practice to erect single wires having an earth return, and to use the cheapest material, i.e. galvanized iron. With the demand for more efficient service, however, transmission requirements generally necessitated the adoption of bronze or copper wires, and the provision, for each subscriber, of a metallic circuit. Stated broadly, with growth came congestion of telephone conductors, especially towards switching centres. Moreover, with growth, the carrying limits of the poles were quickly reached, and open-wire lines became so congested that further expansions could scarcely be contemplated.

It was soon realized that in order to surmount difficulties from congestion, to reduce trouble from storms, and to secure other advantages, it would be necessary ultimately to put the telephone conductors into cable. Early telephone cables were insulated with gutta-percha or india-rubber, but the high electrostatic capacity of those materials severely limited the number of conductors that could be laid up into a cable. Cotton yarn impregnated with an insulating wax or oil and protected by a metallic envelope was tried; so also was paper. Then followed paper lead-sheathed and not impregnated, i.e. air-spaced cable. This development reduced the electrostatic capacity, it diminished the thickness necessary for the dielectric, and in consequence it enabled many more conductors to be carried in a cable of given diameter.

For use within towns for connecting subscribers to exchanges, the weight of a single conductor per statute mile may be 6½ lb., 10 lb., 20 lb., or more, according to the distance to be traversed. In the case of the 6½ lb. type, these conductors are made into cable containing up to about 1 200 pairs. The 10 lb. type may be made into cable of about 900 pairs, and the 20 lb. type into cable of about 400 pairs.

The great bulk of the world's telephone cables consists of comparatively short lengths of the types just described. These short cables, being in towns, are generally laid in ducts.

Simultaneously, with the development of local service between subscribers, just described, the growth of long-distance traffic brought about a state of congestion on pole routes between towns. The first development to relieve congestion was the phantom circuit which made possible an increase of line facilities up to 50 per cent. This was only a partial solution. The introduction of the paper-insulated, air-spaced, lead-covered cable, however, provided means to advance.

Notwithstanding all the advantages of paper as a dielectric, the length of cable through which speech could be commercially transmitted was at first limited to comparatively short distances. It was not until the suggestion by Oliver Heaviside of loading had materialized, that this difficulty was surmounted sufficiently to enable cables to be used for long-distance circuits. Loading consists in the insertion of inductance in series with the line, either "continuously," as a whipping, or "lumped" in the form of coils inserted at definite intervals. Loading of the "continuous" type is restricted chiefly to submarine cables. For long-distance land circuits, loading coils are now almost universal.

With a non-loaded cable, the attenuation rises rapidly with frequency. An important and valuable feature of the improvement due to loading is that, over a wide range of frequency, the attenuation of the loaded circuit is nearly constant.

For a given size of conductor, however, there is in practice a limit to the improvement that can be effected in this manner. This limit is reached when the cable leakance losses and the losses in the loading-coils themselves begin to predominate over the losses in the cable conductors. Further reduction of attenuation in a loaded non-repeatered circuit can only be obtained by providing heavier cable conductors, and loading coils of greater efficiency, which would involve prohibitive cost.

The next step in the development of the long cable circuit was the introduction of a device to replenish the energy in the circuit from an external source at certain space intervals—this device is the telephone repeater.

At first this was an electro-mechanical device, but it soon gave place to the more efficient thermionic-valve type, to which Sir Oliver Lodge has referred.

It might be thought that, with the installation of repeaters, loading would be rendered unnecessary. In practice it is found that the most economical solution of the problem of long-distance transmission is in the combination of the two expedients.

The distance over which a repeatered loaded circuit can be employed is limited by (1) echo currents and (2) transient phenomena. The first limitation, which was encountered on circuits extending beyond 1 000 miles, has been removed by the recently developed echo suppressor. The second limitation has not been encountered up to any length yet contemplated in practice. Phase-compensating devices have, however, been developed with a view to meeting this contingency.

To summarize the present position in regard to the interconnection between long-distance stations, the cases that arise are as follows:

(1) Where open-wire lines are sufficiently free from congestion, both inside and outside towns, to be taken direct to the exchanges.
(2) Where, by means of cables, congestion has to be avoided inside towns, but where open-wire lines are free from congestion outside towns.
(3) Where there are underground cables inside towns, and aerial cables outside.
(4) Where there are underground cables throughout the whole distance between exchanges.

In cases (2), (3) and (4) a quadded type of cable is usual, and the weight of a single conductor per statute mile is either 20 lb. or 40 lb.

In England, long-distance cables are always laid in ducts; in America such cables are more often erected aerially, and on the Continent of Europe they are as a rule armoured and laid direct in the ground. Long-

distance cables are usually made to the required size up to about 150 quads. Such cables when loaded and repeatered have been made to traverse a length of 1 000 miles and there is every reason to believe that this distance could be considerably extended.

Carrier Systems.

Although the idea of increasing the traffic capacity of telegraph lines by applying the principle of frequency discrimination was conceived long ago, it was not until the development of the three-electrode vacuum tube that multiplex systems depending upon frequency discrimination began to assume practical importance. Continuous-wave wireless telephony and wireless telegraphy, which followed the introduction of the three-electrode vacuum tube, found a counterpart in carrier telegraphy and carrier telephony applied to wire lines. A *carrier* is now recognized as being generally an alternating current which may have impressed upon it telegraph or telephone currents. To impress the carrier with the signal characteristics in this manner is to *modulate* it. The reverse process is called *demodulation*.

In telegraphy, modulation may be simply done by interrupting the carrier in accordance with the telegraph signals. In telephony, owing to the complex nature of the voice, no such simple method of modulation is possible.

When operated under suitable conditions, the three-electrode tube has a characteristic such that the output current has one component in linear relation to the input voltage, and others that are not in that relation. Of these others, the most important is proportional to the square of the input voltage, and if the input is sinusoidal it gives rise to a current of frequency double that of the input. Carrier practice is so intimately concerned with frequencies, that for brevity the language relating to this part of the subject during the last decade has extended the meaning of the word "frequency" so that, if required, it shall include the current or voltage to which it appertains.

If the input, instead of consisting of a single frequency, consists of a signal frequency and a carrier frequency, the "square" term in the equation for the output current of the three-electrode tube gives rise not only to currents of double the respective input frequencies, but also to currents of frequencies equal to both the sum and the difference, respectively, of the input frequencies. The chief result of modulation therefore is the production of frequencies corresponding respectively to carrier plus signal, and carrier minus signal.

Again, if the signal itself consists of a band of frequencies, as is the case with speech, there is produced by modulation a band of frequencies on either side of the carrier, each band being of the same width as the originating signal band. These are known as side bands, and they are sometimes considered to be the signal band itself translated in the frequency spectrum.

By employing suitably-selected carrier frequencies, a number of independent signal bands may be translated to different parts of the frequency spectrum and may thereafter be impressed upon a common transmission line, at the receiving end of which they may be separated by means of circuits depending for their operation on frequency discrimination. By a process similar to that employed at the transmitting end, the selected side-band currents may be reconverted into the original signal band.

While in the case of radio receiving circuits it has been usual to employ simple tuned circuits for frequency discrimination, for line carrier systems this is not very satisfactory; for since only relatively low frequencies are suitable for transmission over lines, the various bands must be closely spaced in order to make the best use of the frequency range available. On account of the relatively low carrier frequencies used, the ratio of band width to carrier frequency is large. Consequently, as with tuned circuits all frequencies in the band will not be equally affected, distortion would result. It is therefore the practice to employ electric wave filters which can be designed to select a wide band of frequencies without distortion and to discriminate effectively between closely adjacent frequencies. The development of these wave filters has been one of the principal factors in the success of the present carrier systems.

The following different types of carrier systems are now in use:—

(1) Voice-frequency cable carrier telegraph.
(2) High-frequency open-wire carrier telegraph.
(3) High-frequency open-wire carrier telephone.
(4) High-frequency power-line carrier telephone.

Systems (2) and (3) are suitable for use on open-wire lines to provide traffic channels in addition to those provided by the normal telephone and telegraph circuits. On account of the characteristics of modern loaded cables neither of these systems is suitable for use on underground circuits. For this reason, system (1) has been developed to provide a number of telegraph channels in place of one telephone channel.

The extent to which carrier systems may be employed for increasing the traffic capacity of existing lines depends on the relative cost of providing equivalent facilities by new line construction. This normally limits these systems to distances not less than one or two hundred miles, but cases may arise where they will enable the construction of a new pole route or cable to be deferred for a number of years, in which case they may be justified for considerably smaller distances.

That these systems play an important part in the provision of the world's telephone facilities may be seen from the following table, which gives approximate information concerning high-frequency open-wire carrier systems in service at the end of 1925.

Total number of systems in service	100
Total system mileage	45 000
Total number of telephone channels provided	170
Total number of telegraph channels provided	400
Telephone channel miles	60 000
Telegraph channel miles (duplex)	210 000

The Composite System.

An important step in the direction of economy of line plant has been the development of the so-called

"composite system" in which combined telephone and telegraph operation is secured over the same conductors. The principle involved is frequency discrimination, the composite set being merely a network of inductances and condensers which divides the line into two branches, one for the telephone and another for the telegraph. The two line conductors are connected to two filters, one of which permits only current within the speech range of frequency to pass, and the other permits only frequencies between zero and about 80 cycles per second to pass. Fast hand-speed telegraph working is only about 16 cycles per second. Speech, as usually transmitted by telephone, covers a range of the order 200 cycles to 2 500 cycles per second, and it is because of this distinction that the separation of the telephone and the telegraph currents is practicable.

The composite system is in daily use over the longest circuits in the United States, and more than 600 000 miles of telegraph circuits in accordance with this system are in operation. The average length of the circuits is about 700 miles, and one circuit is over 4 000 miles with 17 repeater stations intervening.

The composite system differs from the high-frequency carrier telegraph or telephone system in that the superposed communication in the composite system occupies a range of frequencies *below* that occupied by speech, instead of *above* as in the case of carrier systems. It is possible in practice to operate the composite system and the carrier system simultaneously on the same conductors.

The Transmission of Pictures over Telephone Lines.

Ever since the introduction of the electric telegraph many investigators have endeavoured to develop a system whereby facsimiles of documents or of photographs might be obtained at a distant station by electrical transmission. The simpler of the systems arrived at usually involve an application of the principle of the electric telegraph in which the received record is a series of dots and dashes, constituting a two-tone record of black and white, where the dark and light greys are effectively obtained by the spacing of the dots as in newspaper photographic reproductions. In many cases these processes give good results, but they fail to provide the fine detail and resolution of a good photograph.

Good resolution entails the transmission of rapid changes of illumination, i.e. of relatively high frequencies. For this fundamental reason, telephone circuits have been found to be suitable as transmission media.

Telephoto systems consist essentially of a light-sensitive cell upon which are incident light rays that vary in intensity with the density of a slowly moving photographic transparency of the subject-matter to be transmitted. In some cases the light-sensitive cell and the photographic transparency have been replaced by a moving coil with an attached stylus that traverses a chemical depth-record of the subject-matter. After amplification, the minute voltage variations set up in the photo-electric cell, or similar apparatus, are transmitted to the receiving end, where they are caused to control the light emitted from some fixed source. This control arrangement may be regarded as a light valve. Light thus controlled, in accordance with the density of the original, is caused to act upon a photographic blank which moves in synchronism with the sending-end record. The result is a photographic reproduction of the original.

The light valve may take the form of a string galvanometer—a moving-coil oscillograph—or it may be an electro-optical device, utilizing the phenomenon of electrical double refraction in a manner similar to the decomposition of polarized light into two components of different velocity of propagation. Difficulties at first presented themselves with reference to the construction and adjustment of the apparatus, and the maintenance of synchronism. Persistent efforts, however, have so successfully solved the problems, that to-day there are in Europe and America several systems in commercial operation. Pictures have in this manner been transmitted satisfactorily over telephone lines for more than 3 000 miles. With radio-transmission, chiefly on account of the properties of the transmitting medium, the results have been less perfect.

Wireless Telephony.

At the meeting of the British Association in 1882, attention was directed to a telephone receiver which had then recently been devised by Prof. A. E. Dolbear. The instrument depended entirely upon electrostatic forces, and it consisted simply of two metal diaphragms rigidly fixed parallel to one another, close together, but not touching, in an insulated case of ebonite. When telephonic voltages were applied to the diaphragms, sonorous vibrations were obtained, with consequent reproduction of speech. The fact that the empty space between the diaphragms was traversed by telephonic impulses, may have suggested the extension of this distance.* Twenty years later R. A. Fessenden obtained a patent for voice modulation of nearly continuous waves, and he led the way to the present wireless carrier system. Throughout the world, investigators then attacked the problem in various ways. Success of a decisive character was achieved in 1912 by Prof. Giuseppe Vanni, of Rome, who transmitted speech sounds by wireless telephony between Rome and Treviso (420 km), and between Rome and Tripolo (1 000 km). In the following year it was announced that German experimenters had established wireless telephony between Berlin and Nauen. These and many other endeavours culminated on the 30th September, 1915, in the transmission of speech and music from the United States naval establishment at Arlington (Washington) to Honolulu. On the 23rd October, 1915, a successful demonstration was given of radio-telephone transmission from Arlington to Paris.

In principle, wireless telephony differs from carrier transmission over wires in little else than in the fact that it employs a different medium and higher carrier frequencies. It consists first in the production of a carrier wave of limits in practice usually of the order of between 50 and 15 000 kilocycles a second. The power delivered to the antenna varies from a few watts to several hundred kilowatts. The modulation of this carrier wave in accordance with speech waves is effected

* See *Journal of the Society of Telegraph Engineers and of Electricians*, 1882, vol. 11 p. 130.

by means of a microphone which, in powerful transmitters, is associated with vacuum tube amplifiers by means of which the voice currents are built up in successive stages until they become sufficiently powerful to control the radio carrier wave. Modulation of the carrier in wireless telephony produces two bands of waves, one of lower and the other of higher frequency than the carrier. In the ordinary method of transmission, as used for example when broadcasting, all these three components, i.e. the carrier and the two side-bands, are impressed upon the antenna and are radiated. It is generally considered that the carrier component itself contains two-thirds of the total energy transmitted. The two side-bands together occupy twice the frequency range needed for the transmission of all audible sounds.

In the high-power transatlantic radio-telephone station, at present under test, a new system of transmission is adopted in which only one side-band is radiated. The carrier and the undesired side-band are suppressed at the transmitting station and the amount of carrier necessary to render the signal audible is re-introduced by a local oscillator at the receiving station. Besides the high efficiency obtained in consequence of this suppression, the system has other advantages. The effects of fading are reduced, and the problem of designing a satisfactory antenna is made less difficult. The vacuum tubes at the Rugby station, in the last stage of the radio transmitter, are of the 10 kW water-cooled type. The final stage of amplification is effected by two groups each containing 15 of these high-power tubes. This station made possible the provision of two-way telephonic conversation—trustworthy and continuous—across the Atlantic: a task successfully accomplished for the first time on Sunday, 7th February, 1926, and publicly demonstrated a month later, just 50 years after the establishment of Graham Bell's invention on a practical basis—a fitting tribute to his imperishable memory.

Bibliography to Appendix III.

The following list of books relating to telephony includes some standard treatises. Most of them contain references to papers relating to the various branches of the subject in technical and scientific journals.

J. E. Kingsbury: "The Telephone and Telephone Exchanges."
H. N. Casson: "The History of the Telephone."
F. G. C. Baldwin: "History of the Telephone in the United Kingdom."
U.S.A. Bureau of Standards Circular No. 112; "Telephone Service."
T. H. Blakesley: "Alternating Currents of Electricity."
O. Heaviside: "Electrical Papers."
O. Heaviside: "Electromagnetic Theory."
F. Breisig: "Theoretische Telegraphie."
J. A. Fleming: "The Propagation of Electric Currents in Telephone and Telegraph Conductors."
A. E. Kennelly: "The Application of Hyperbolic Functions to Electrical Engineering Problems."
H. W. Malcolm: "The Theory of the Submarine Telegraph and Telephone Cable."
J. G. Hill: "Telephonic Transmission."
K. S. Johnson: "Transmission Circuits for Telephonic Communication."
M. P. Weinbach: "Principles of Transmission in Telephony."
A. B. Smith and W. L. Campbell: "Automatic Telephony."
W. Aitken: "Automatic Telephone Systems."
T. E. Herbert: "Telephony."
W. Aitken: "Manual of the Telephone."
C. A. Wright and A. F. Puchstein: "Telephone Communication."
E. Ekeberg: "Telefoni."
A. E. Kennelly: "Electrical Vibration Instruments."

THE MAGNETIC FIELD OF THE DYNAMO-ELECTRIC MACHINE.*

By F. W. CARTER, M.A., Sc.D., Member.

(*Paper first received* 16*th January, and in final form* 25*th February,* 1926.)

SUMMARY.

The first portion of the paper is for the most part written around the subject of the reluctance of the magnetic circuit, particularly of the air-gap and teeth. Other matters are, however, referred to, such as that of the shape of the curve of flux traversed by the armature conductors, and that of the flux variation along the pole-face. Much of the analysis was indeed originally developed with other ends in view, such as the determination of harmonics in the e.m.f. wave, of losses in the pole-face and elsewhere, or the investigation of the cause of noises and like incidental effects of the magnetic changes. These are for the most part particular applications of the analysis.

The determination of the reluctance of the gap is made to depend on two factors; one, an equivalent length, which has, in the normal portion of the gap, the same reluctance per unit area as the actual gap; the other, an equivalent area, made up of the area of the radial projection of the normal gap on the cylindrical surface midway between armature and field, with additions for the fringe effects at the boundaries, and, where necessary, reductions to take account of ducts and band recesses. The magnetization of teeth is also discussed.

The second part of the paper deals particularly with slots in which conductors carrying currents are located. The subjects of distributed excitation and of the reaction of the load on the exciting field are here discussed. Finally the reactance of the imbedded conductors is investigated.

A number of Appendices deal with details of the calculations.

(1) INTRODUCTION.

The designer of electrical machinery usually endeavours, in his primary calculations, to follow a rational scheme, based on sound physical assumptions; but in many secondary matters he is compelled to resort to methods of an empirical or imperfectly reasoned nature, which in some instances have little relation to facts. In reality he relies on his experience to bring the performance of the machine sufficiently near to his purpose to be within the limits of toleration permitted to him. It is the object of the present paper to examine some of the secondary problems of design, and to establish the calculations as far as possible on a rational basis, with the double purpose of assisting the designer and of elucidating some of the more recondite actions of the machinery. The problems which form the subject of the paper are concerned with the magnetic field, which it is proposed to discuss with greater particularity than has hitherto been attempted.

A large part of the paper is based on the use of conjugate functions in the solution of two-dimensional problems involving equipotential and flux-line boundaries.* Such use has long been current among physicists, but it seems to have been reserved for the author to initiate their application to practical problems of machine design,† and some of his results are now in general use among designers. Other results have been established at various times but not hitherto published, while others have been developed to give completeness to the present paper. Certain problems germane to the subject but using other methods are also discussed.

It need hardly be pointed out that a solution of so complicated a magnetic problem as is presented by an

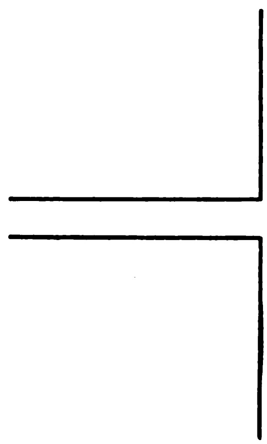

FIG. 1.

electric machine is not attainable. The most that can be expected is that the problem may be divisible, and a number of solutions obtainable, each substantially correct in a limited region. Here, however, an obvious precaution may be mentioned; it is not possible to combine such partial solutions unless, in the neighbourhood of the common boundary of any two of the limited regions considered, the lines of force and equipotential lines may, without sensible error, be considered as belonging indifferently to either of the regions. Neglect of this has led to the publication of some very misleading results.

Another matter to which attention may be directed arises from the fact that, in most practical problems, some of the boundaries have to be assumed to extend to infinity in certain directions; and, in most cases, the total flux dealt with is infinite. Unless, therefore,

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* See MAXWELL: "Electricity and Magnetism," ch. 12; and JEANS: "Electricity and Magnetism," ch. 8, par. 306 *et seq.*; see also Appendix I.

† F. W. CARTER: "Note on Air-Gap and Interpolar Induction," *Journal I.E.E.*, 1900, vol. 29, p. 925; also "Air-Gap Induction," *Electrical World and Engineer*, 1901, vol. 38, p. 884.

the boundaries can be so arranged that the portion of the flux with which the problem is concerned is localized and suitably delimited, the solution is a matter of judgment rather than of calculation. Consider, for instance, the case of an iron-core reactance having an air-gap. The edge of the gap may be represented by a pair of opposing faces, with flanks extending to infinity (Fig. 1), and the field near the gap may be computed from this representation. The flux in the gap becomes uniform at a short distance from the edge, and this portion of the field presents no difficulty. But the fringe flux is infinite in amount, and has no natural limit short of infinity. A general solution is therefore impossible in this case; the whole magnetic circuit is involved in the problem, which is thus of a particular nature and outside the purpose of the present paper (see Appendix 2).

(2) Curvature of Surfaces.

The problems to be considered are concerned with regions bounded by planes; whereas the actual regions are in most cases bounded, in part, by cylindrical surfaces. In some of the problems the region under consideration occupies so small a fraction of the circumference that the curvature is negligible. In others, as in the interpolar fringe, the divergence is only sensible where the field is weak, so that its effect is small. The determination of the reluctance of the air-gap, however, presupposes a radius on which its area is measured, and the chief effect of curvature is provided for in the proper choice of this radius.

Consider the case of a smooth armature of radius a and at potential zero, surrounded concentrically by a smooth field of radius $a + g$, at unity potential. The potential function is

$$\phi = \frac{\log \dfrac{r}{a}}{\log \left(\dfrac{a+g}{a}\right)} \quad . \quad . \quad . \quad . \quad (1)$$

The total flux is $2\pi/\log [(a + g)/a]$, and, if this be written $2\pi R/g$,

$$R = \frac{g}{\log\left(1 + \dfrac{g}{a}\right)}$$
$$= a + \tfrac{1}{2}g \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

when g/a is small. Thus the area should be reckoned at the middle of the air-gap. This, however, does not settle the question when one or both of the opposing surfaces are slotted, for the gap has then to be defined. The following may serve to throw light on the matter.

Assume, as potential function :—

$$\phi = \frac{c \log \dfrac{r}{c-\frac{1}{2}g} + \frac{1}{2}\lambda g\left[\left(\dfrac{r}{c-\frac{1}{2}g}\right)^{n} - \left(\dfrac{r}{c-\frac{1}{2}g}\right)^{-n}\right]\cos n\theta}{c \log \dfrac{c+\frac{1}{2}g}{c-\frac{1}{2}g} + \frac{1}{2}\lambda g\left[\left(\dfrac{c+\frac{1}{2}g}{c-\frac{1}{2}g}\right)^{n} - \left(\dfrac{c+\frac{1}{2}g}{c-\frac{1}{2}g}\right)^{-n}\right]} \quad (3)$$

This, with a certain limitation in the size of the constant λ, and with n a whole number, gives the distribution between a pair of concentric boundaries, the inner one smooth, of radius $c - \frac{1}{2}g$, and at zero potential; the outer one corrugated, of minimum radius $c + \frac{1}{2}g$, and at unity potential. The denominator of ϕ in (3) is, to the second order in g/c—which may be assumed small—

$$g\left[1 + \lambda \sinh \frac{ng}{c}\right] \quad . \quad . \quad . \quad . \quad (4)$$

The mean value of the radial force at radius c is accordingly, to the second order in g/c

$$\frac{1}{g\left[1 + \lambda \sinh \dfrac{ng}{c}\right]} \quad . \quad . \quad . \quad . \quad (5)$$

The quantity designated the equivalent gap in this paper, is the reciprocal of the mean value of radial force per unit difference of potential between the sides of the gap, when the radius is made infinite. Calling this quantity G, in the present instance

$$G = g\left[1 + \lambda \sinh \frac{ng}{c}\right] \quad . \quad . \quad . \quad (6)$$

If R is the radius sought, the total flux is

$$\frac{2\pi R}{G} = \int_0^{2\pi} \frac{d\phi}{dr} r\, d\theta = \frac{2\pi c}{g\left[1 + \lambda \sinh \dfrac{ng}{c}\right]} \quad . \quad . \quad (7)$$

Accordingly $R = c$, or the area of the field should be reckoned at the middle of the minimum gap. The problem is, of course, a particular one, furnishing evidence rather than proof of the conclusion as applied to machine design.

(3) Equivalent Gap with One Surface Slotted.

In the *Electrical World* article cited on page 1115, the equivalent gap, or the uniform gap having the same mean reluctance per unit area as the slotted gap, was deduced from the consideration of a single slot, of width s and of infinite depth, in one of the opposing equipotential surfaces (see Fig. 2). The effect of the slot was shown to be equivalent to annulling a certain fraction, σ, of its width given by

$$\sigma s = \frac{2}{\pi}\left\{s \arc\tan\left(\frac{s}{2g}\right) - g \log\left[1 + \left(\frac{s}{2g}\right)^2\right]\right\} \quad (8)$$

Accordingly, if t is the width of the tooth (at the crown), and G the equivalent gap

$$\frac{t+s}{G} = \frac{t+s-\sigma s}{g} \quad . \quad . \quad . \quad . \quad (9)$$

or

$$G = \frac{t+s}{t+s-\sigma s} g \quad . \quad . \quad . \quad . \quad (10)$$

The curve connecting σ and s/g is reproduced in Fig. 3.

The transformation between the plane of z and the plane of ζ may be written:

$$z = \frac{g}{\pi}\int\frac{\sqrt{[(\zeta+\lambda)(\zeta+\lambda^{-1})]}}{\zeta(\zeta+1)}d\zeta$$
$$= \frac{1}{\pi}\left\{g\left[\operatorname{arc\,cosh}\frac{2\zeta+\lambda+\lambda^{-1}}{\lambda-\lambda^{-1}} - \operatorname{arc\,cosh}\frac{2\zeta^{-1}+\lambda+\lambda^{-1}}{\lambda-\lambda^{-1}}\right] + s\operatorname{arc\,cos}\left(\frac{1-\zeta}{1+\zeta}\cdot\frac{\lambda-1}{\lambda+1}\right)\right\} \quad . \quad (11)$$

in which
$$\frac{s}{g} = \lambda^{\frac{1}{2}} - \lambda^{-\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

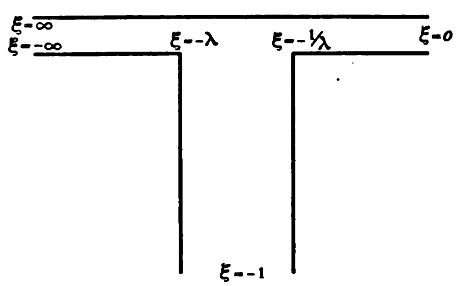

FIG. 2.

The force at the pole-face is given by

$$F = \frac{1+\zeta}{g[(\zeta+\lambda)(\zeta+\lambda^{-1})]^{\frac{1}{2}}} \quad . \quad . \quad . \quad (13)$$

the location being given in terms of the same parameter ζ by equation (11). The variation of this force is accordingly from a maximum of $1/g$ to a minimum of $1/g[1+(s/2g)^2]^{\frac{1}{2}}$. This has an important application in the computation of the pole-face losses.*

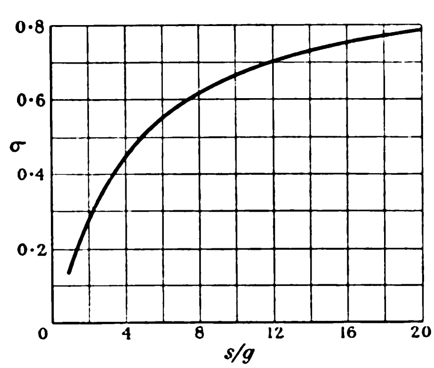

FIG. 3.

The solution thus obtained, although based on an unattainable ideal, satisfies fully the needs of the designer. It is true that the slot is assumed of infinite depth; but, inasmuch as the field hardly penetrates beyond the mouth, this is of no consequence. In the case of partially closed slots, indeed, s should be taken as the width at the mouth. The region considered has been cut off on each side at the position of the centre of the tooth, and other regions of half tooth and slot applied, thus introducing some discontinuity in the field. It is possible, however, to give a solution which avoids the discontinuity, and thereby to show that it is of little consequence.

The problem now proposed is that of determining the field between the plane and slotted equipotential surfaces shown in Fig. 4. A feature of the problem is that the median lines of tooth and slot, where they cross the gap, are flux lines; and the area bounded by these lines, by the half tooth and the plane equipotential, can be segregated without altering the problem.

Consider the range of points C′, B′, A′, O, A, B, C on the real axis, shown in Fig. 5, these being disposed symmetrically about O. Write k for OA/OB, and sn α for OB/OC. The transformation

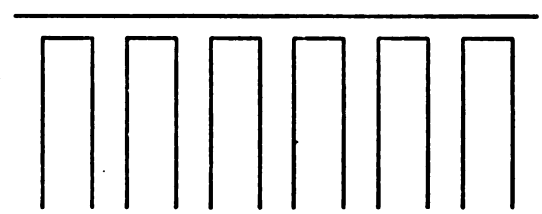

FIG. 4

$$z = M\int\left(\frac{1-k^2\zeta^2}{1-\zeta^2}\right)^{\frac{1}{2}}\frac{d\zeta}{1-k^2\operatorname{sn}^2\alpha\zeta^2} \quad . \quad . \quad (14)$$

converts the half-plane of ζ into the plane of z bounded as shown in Fig. 6.

The field determined by

$$\chi = \phi + j\psi = \frac{1}{F}\int\frac{d\zeta}{[(1-\zeta^2)(1-k^2\operatorname{sn}^2\alpha\zeta^2)]^{\frac{1}{2}}} \quad . \quad (15)$$

in which ϕ is the potential function and ψ the flux function, represents a system in the plane of ζ (Fig. 5) in which AC and A′C′ are at equal and opposite unity potentials, in which AA′ is a flux line and C ∞ C′ also a flux line.* In the plane of z accordingly (Fig. 6) AA′ and CC′ are flux lines, and ABC, A′B′C′, equi-

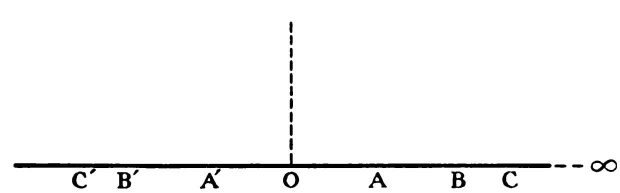

FIG. 5.—Plane of ζ.

* F. W. CARTER: "Pole-Face Losses" *Journal I.E.E.* 1916, vol. 54, p. 168.

* This, as a problem in electrostatics, is discussed in J. J. Thomson's "Recent Researches in Electricity and Magnetism," ch. 3, par. 245. The field in the plane of z is plotted in a paper entitled "The Calculation of Air-space Flux," by Prof. W. Cramp and Miss N. I. Calderwood, *Journal I.E.E.*, 1923, vol. 61 p. 1063.

potentials at equal and opposite unity potentials. The total flux between ABC and A′B′C′ is:

$$\psi_0 = \frac{1}{F}\int_1^{1/k\,\mathrm{sn}\,\alpha} \frac{d\zeta}{[(\zeta^2-1)(1-k^2\,\mathrm{sn}^2\,\alpha\,\zeta^2)]^{\frac{1}{2}}}$$

$$= \frac{F'}{F} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

The change in z as ζ passes through C is [see equation (14)]:—

$$\tfrac{1}{2}js = M\frac{\pi}{2}\cdot\frac{\mathrm{cn}\,\alpha}{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}j \quad . \quad . \quad . \quad (17)$$

The change in z between O and B is, writing $\zeta = \mathrm{sn}\,u$ in equation (14),

$$g+\tfrac{1}{2}jt$$

$$= M\int_0^{K+jK'} \frac{1-k^2\,\mathrm{sn}^2\,u}{1-k^2\,\mathrm{sn}^2\,\alpha\,\mathrm{sn}^2\,u}du$$

$$= M\left\{K+jK' - \int_0^{K+jK'} \frac{k^2\,\mathrm{cn}^2\,\alpha\,\mathrm{sn}^2\,u}{1-k^2\,\mathrm{sn}^2\,\alpha\,\mathrm{sn}^2\,u}du\right\}$$

$$= M\left\{K+jK' - \frac{\mathrm{cn}\,\alpha}{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}\Pi(K+jK',\alpha)\right\}$$

$$= M\left\{K+jK' - \frac{\mathrm{cn}\,\alpha}{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}\left[(K+jK')Z(\alpha)+j\frac{\pi}{2}\cdot\frac{\alpha}{K}\right]\right\} \quad (18)$$

From equation (15) we have

$$\frac{d\chi}{d\zeta} = \frac{1}{F}\cdot\frac{1}{[(1-\zeta^2)(1-k^2\,\mathrm{sn}^2\,\alpha\,\zeta^2)]^{\frac{1}{2}}}$$

From equation (14)

$$\frac{dz}{d\zeta} = M\left(\frac{1-k^2\zeta^2}{1-\zeta^2}\right)^{\frac{1}{2}}\frac{1}{1-k^2\,\mathrm{sn}^2\alpha\zeta^2}$$

Whence
$$\frac{d\chi}{dz} = \frac{1}{MF}\left(\frac{1-k^2\,\mathrm{sn}^2\,\alpha\,\zeta^2}{1-k^2\zeta^2}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (23)$$

in which, if absolute values are required, the value of M may be written [equation (18)]

$$M = \frac{g}{K\left[1-\frac{\mathrm{cn}\,\alpha}{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}Z(\alpha)\right]} \quad . \quad . \quad (24)$$

The imaginary axis in Fig. 5, which is the equipotential line at zero potential, becomes the unslotted pole-face in Figs. 4 and 6. Equation (23), in which $\zeta = j\eta$, gives the density of the field at this face, the position being given by equation (14). Opposite the centre of the tooth ($\eta = 0$) the field is at its maximum, and opposite the centre of the slot ($\eta = \infty$) at its minimum. The ratio of the minimum to maximum field is therefore as $\mathrm{sn}\,\alpha : 1$.

The chief difficulty in applying the results of this investigation lies in the determination of k and α to give specified proportions to the parts, through equations (19) and (20). Fortunately, the previous investigation differs so little in its results from the present that, in any ordinary case, a close approximation to k and α is immediately deducible from it. Thus, comparing equations (9) and (21):

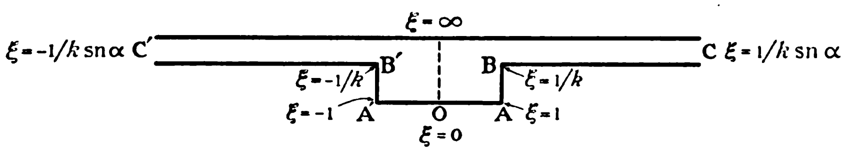

FIG. 6.—Plane of z.

whence
$$\frac{2g}{s} = \frac{2}{\pi}K\left[\frac{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}{\mathrm{cn}\,\alpha} - Z(\alpha)\right] \quad . \quad . \quad (19)$$

$$\frac{t}{s} = \frac{2}{\pi}K'\left[\frac{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}{\mathrm{cn}\,\alpha} - Z(\alpha)\right] - \frac{\alpha}{K} \quad . \quad . \quad (20)$$

If G is the equivalent gap [equation (16)]

$$\psi_0 = \frac{F'}{F} = \frac{t+s}{2G} \quad . \quad . \quad . \quad . \quad (21)$$

and the slot factor, or gap coefficient, is

$$\frac{G}{g} = \frac{F}{F'}\cdot\frac{t+s}{2g}$$

$$= \frac{F}{F'}\left\{\frac{K'}{K}+\frac{\pi}{2}\cdot\frac{1-\frac{\alpha}{K}}{\frac{\mathrm{sn}\,\alpha\,\mathrm{dn}\,\alpha}{\mathrm{cn}\,\alpha}-Z(\alpha)}\right\} \quad . \quad . \quad (22)$$

It should be noted that the modulus of the complete elliptic integrals F and F' is $k\,\mathrm{sn}\,\alpha$, all other elliptic functions having modulus k.

$$\frac{t+s}{2G} = \frac{F'}{F} = \frac{t+s-\sigma s}{2g} \quad . \quad . \quad . \quad (25)$$

and from a table of complete elliptic functions the modulus, $k\,\mathrm{sn}\,\alpha$, can be found. Again, from equations (13) and (23) we find, by considering the ratio of the minimum to maximum field,

$$\mathrm{sn}\,\alpha = \left[1+\left(\frac{s}{2g}\right)^2\right]^{-\frac{1}{2}} \text{ approx.} \quad . \quad . \quad (26)$$

A specimen calculation is given in Appendix 3.

(4) EQUIVALENT GAP WITH BOTH SURFACES SLOTTED.

When both of the opposing equipotential surfaces are slotted, the problem is complicated, and an exact solution hardly to be expected. This case was discussed

in a short article contributed to the *Electrician* some years ago,* but the reasoning is here presented more fully. It assumes the disturbance produced by a slot to be strictly local, a condition sensibly fulfilled, for the purpose in view, in most cases, and notably in the large class in which the air-gap is small and the slot in one of the members semi-closed.

If s_1 and s_2 are the widths of the opposing slots, the

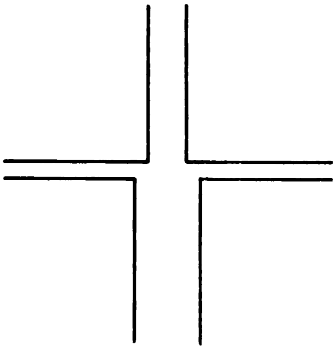

FIG. 7.

amount of periphery that must be annulled to allow for the slots when exactly opposing, as in Fig. 7,† is

$$w=\frac{2}{\pi}\left\{\frac{s_1+s_2}{2}\arctan\frac{s_1+s_2}{2g}+\frac{s_1-s_2}{2}\arctan\frac{s_1-s_2}{2g}\right.$$
$$\left.-\frac{g}{2}\log\left[1+\left(\frac{s_1+s_2}{2g}\right)^2\right]\left[1+\left(\frac{s_1-s_2}{2}\right)^2\right]\right\} \quad (27)$$

If w_1 and w_2 are given by the same equation with s_2 and s_1 put zero in turn,‡ $w_1 + w_2$ is the amount that must be annulled when the slots are remote from one

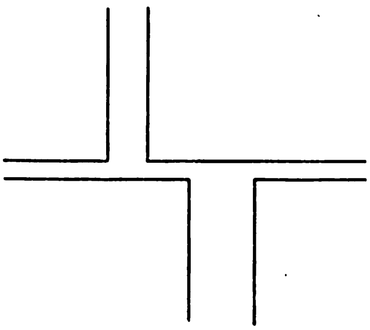

FIG. 8.

another (Fig. 8). The total decrease in the permeance of the gap as the slots are displaced from opposite to remote relation is accordingly $(w_1 + w_2 - w)/g$; and the curve of variation plotted against displacement takes the general form of Fig. 9. If the area of this curve be divided by the total variation of the ordinate, a linear magnitude c is determined which is such that, for the purpose in view, the slots may be considered opposite as long as their centres are not more than $\frac{1}{2}c$ apart, and remote for the remainder of the pitch. If a_1, a_2 are the slot-pitches in the two members respectively, c/a_1 is the proportion of slots of the second member that are opposite those of the first; and $c/(a_1a_2)$ the number of opposite slots per unit length of periphery, the remainder, or $(1/a_2) - [c/(a_1a_2)]$, being remote.

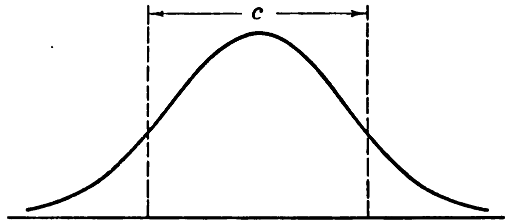

FIG. 9.

The unit length is therefore diminished in effect to the value—the reciprocal of the air-gap coefficient—

$$\begin{aligned}\frac{1}{k} &= 1-\left(\frac{1}{a_1}-\frac{c}{a_1a_2}\right)w_1-\left(\frac{1}{a_2}-\frac{c}{a_1a_2}\right)w_2-\frac{c}{a_1a_2}w\\ &=\left(1-\frac{w_1}{a_1}\right)\left(1-\frac{w_2}{a_2}\right)+\frac{c(w_1+w_2-w)-w_1w_2}{a_1a_2}\\ &=\frac{1}{k_1k_2}+\frac{c(w_1+w_2-w)-w_1w_2}{a_1a_2} \quad . \quad . \quad . \quad . \quad (28)\end{aligned}$$

where k_1, k_2 are the respective gap coefficients of the members when the other is assumed unslotted.

FIG. 10.—Plane of ζ.

The calculation of c in the general case of rectangular slots in the members is hardly practicable; but an analogous problem of gaps in opposing planes probably meets all requirements.

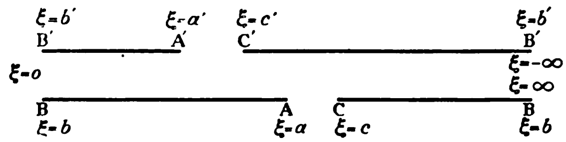

FIG. 11.—Plane of z.

The transformation

$$z=\int\frac{(\zeta-a)\,(\zeta-c)\,(\zeta-a')\,(\zeta-c')}{\zeta(\zeta-b)^2\,(\zeta-b')^2}d\zeta \quad . \quad (29)$$

with the relations *

$$\left.\begin{aligned}\frac{1}{b-a}+\frac{1}{b-c}+\frac{1}{b-a'}+\frac{1}{b-c'}-\frac{1}{b}-\frac{2}{b-b'}=0\\ \frac{1}{b'-a}+\frac{1}{b'-c}+\frac{1}{b'-a'}+\frac{1}{b'-c'}-\frac{1}{b'}-\frac{2}{b'-b}=0\end{aligned}\right\}(30)$$

convert the positive half-plane of ζ (Fig. 10) into the plane of z (Fig. 11); and, together with the field functions,

$$\phi + j\psi = \frac{j}{\pi}\log\zeta \quad . \quad . \quad . \quad . \quad (31)$$

* *Electrician*, 1918, vol. 81, p. 400.
† F. W. CARTER: "Magnetic Centering of Dynamo-Electric Machinery," *Minutes of Proceedings of the Institution of Civil Engineers*, 1911–12, vol. 187, p. 311.
‡ See equation (8).

* These are the conditions that the pairs of lines AB, BC, and A′B′, B′C′ are respectively collinear.

gives the required solution; viz. a pair of equipotential planes, differing in potential by unity, in which are gaps of dimensions and location depending on the values of the constants. For the designer's purpose, however, the result is of small value, as the connection between his data and the constants is too involved.

The problem is simplified when the gaps in the opposing planes are equal. In this case

$$ac' = a'c = bb'$$

and the two relations of equations (30) become identical. The data are now expressible in terms of two quantities, and by a process of cross-plotting the curve of variation of flux can be obtained. The calculation is somewhat tedious and need not be reproduced here. A few cases have been worked out and the results are given in Table 1, together with the numerator of the last term in equation (28).

TABLE 1.

$\frac{s}{g}$	$\frac{c}{s}$	$\frac{c(w_1+w_2-w)-w_1w_2}{s^2}$
2	1·25	0·061
3	1·13	0·088
4	1·07	0·099

As a typical case, assume $a_1/s = 2$, $a_2/s = 2·5$; Table 2 gives the gap coefficients, k_1 and k_2 from equation (10) and k from equation (28): k_1k_2 and $k_1 + k_2 - 1$, which may be regarded as approximations to k, are also given. It would seem that the approximation $k = k_1 + k_2 - 1$, is the better, although tending a little towards the low side. Designers generally appear to favour the approximation $k = k_1k_2$.

TABLE 2.

$\frac{s}{g}$	k_1	k_2	k	k_1k_2	k_1+k_2-1
2	1·16	1·125	1·285	1·305	1·285
3	1·23	1·175	1·41	1·445	1·405
4	1·29	1·22	1·525	1·575	1·51

(5) RELUCTANCE OF TEETH.

The present paper deals for the most part with the field in air-spaces; but the subject of the reluctance of the teeth is a cognate one, and moreover necessary to the discussion on account of its reaction on the field in the gap. Where the flux density in the tooth is low, the magnetizing force required is insignificant compared with that needed for the air-gap; and the usual designers' rule of treating the density as uniform at its value one-third of the distance from the root of the tooth allows approximately for the varying saturation. But where, as in the class of machinery with the design of which the author has been most closely associated,* the density at the root of the tooth may amount to 27 000 lines per cm^2, the magnetizing force required for the teeth is comparable with that needed for the gap, and a more reasonable practice is desirable. The author has used the following method since 1912,* with results which agree very well with experience.

Before entering upon the discussion, however, it is expedient to dispose of a small matter of detail. This is the effective length of the teeth, particularly those on the outside of the cylindrical surface. It is usual to consider only the portion between crown and root of the tooth; thus, in the case of outside teeth, extending the problem to the point where the magnetic density is greatest, and no further. It is more reasonable, for the present purpose, to assume that the tooth extends to where the density is reduced to the value it has at the crown. In Fig. 12, if n is the number of teeth in the periphery, l the length from crown to root, l' the effective length, t and r the widths at crown and root

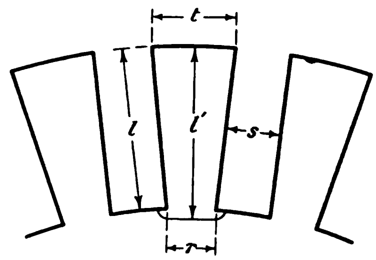

FIG. 12.

respectively, then, in accordance with the above assumption,

$$t = r + (l' - l)\left(\pi - \frac{2\pi}{n}\right) \quad . \quad . \quad . \quad (32)$$

but

$$\frac{(t-r)}{l} = \frac{2\pi}{n} \quad . \quad . \quad . \quad . \quad . \quad (33)$$

hence

$$l' = l + l\frac{2\pi}{n} \cdot \frac{n}{(n-2)\pi} = \frac{n}{n-2}l \quad . \quad (34)$$

When the flux density in the teeth is great, an appreciable flux is carried in the slots. It is usually assumed by designers that this can be computed by taking the difference in magnetic potential between the pole-face and bottom of slot, and dividing by the distance which separates these parts. This is far from being a reasonable assumption; the greater part of the difference of potential is used in the interval between the pole-face and level of the tooth crowns, in which the field follows closely that computed on the assumption of infinite permeability in the iron. The field in the slot consists chiefly of leakage lines from sides to bottom. The strength of the field at any level in the slot may be deduced approximately from the consideration that the tangential magnetic force is continuous through the side of the slot. Thus, in Fig. 12, if w is the width of the tooth at any level, s the (constant) width of the

* Railway motors. The figure given is computed in the conventional manner, i.e. on the assumption that the whole flux passes in the iron.

* The subject was recently discussed in a somewhat similar manner by J. ROCHE: "Détermination des Ampère-tours nécessaires à l'Alimentation des Dents et des Pertes dans les Dents," *Revue Générale de l'Électricité*, 1923, vol. 13, p. 563. See also W. B. HIRD: "The Reluctance of the Teeth in a Slotted Armature," *Journal I.E.E.*, 1900, vol. 29, p. 933

slot, B the density in the iron, H the corresponding magnetic force, and λ the ratio of iron volume to core volume (usually about 0·9 for 0·625 mm laminations), then

$$N = [\lambda B + (1 - \lambda)H]w + Hs \quad . \quad . \quad (35)$$

represents the flux carried by one tooth and slot, per unit length of core; and this, under the pole, is constant from top to bottom of the tooth. The quantity $\lambda B + (1 - \lambda)H$ is immediately deducible from the B, H curve of the iron (Fig. 13) and represents the average flux density in the laminated structure. It is here designated B', and equation (35) may be written

$$N = B'w + Hs \quad . \quad . \quad . \quad . \quad (36)$$

Using the same notation as before, viz. l for length of tooth, t and r for width of crown and root respectively, the distance x of the section w from the crown is given by

$$\frac{x}{l} = \frac{t - w}{t - r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

Eliminating w from equation (36) we get

$$B'\left[t - \frac{x(t - r)}{l}\right] + Hs = N$$

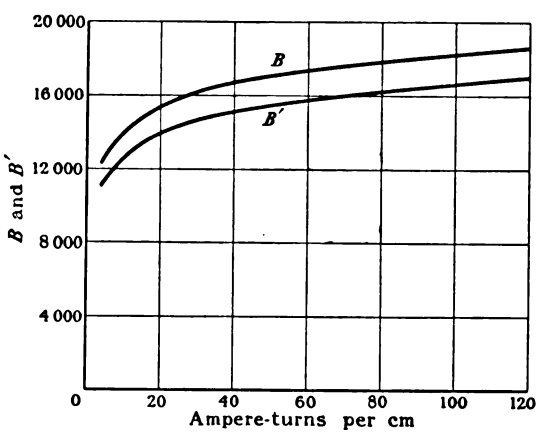

FIG. 13.

Whence

$$- B'\frac{t - r}{l}dx + (N - Hs)\frac{dB'}{B'} + s\,dH = 0$$

and

$$\int H\,dx = \frac{l}{t - r}\left\{\int \frac{NH - sH^2}{(B')^2}dB' + s\int \frac{H}{B'}dH\right\}$$

$$= \frac{l}{t - r}\left\{N\int \frac{H\,dB'}{(B')^2} + s\left[\frac{H^2}{B'} - \int \frac{H\,dH}{B'}\right]\right\} \quad (38)$$

This gives the magnetomotive force required for the teeth, the limits of the integrals corresponding to root and crown respectively. It has been shown [equation (33)] that $l/(t - r)$ is equal to $n/(2\pi)$, and the equation may be written, for inside teeth,

$$\int H\,dx = \frac{n}{2\pi}\left\{N\int \frac{H\,dB'}{(B')^2} + s\left[\frac{H^2}{B'} - \int \frac{H\,dH}{B'}\right]\right\} \quad (39)$$

For outside teeth, as already shown, there is a further small region of high density, in which the same conditions occur in inverse order, and l' should be written for l in equation (38). The appropriate equation for outside teeth is accordingly

$$\int H\,dx = \frac{n^2}{2\pi(n-2)}\left\{N\int \frac{H\,dB'}{(B')^2} + s\left[\frac{H^2}{B'} - \int \frac{H\,dH}{B'}\right]\right\} \quad (40)$$

The values of B' and H corresponding to any value of w are readily obtained as the intersection of the

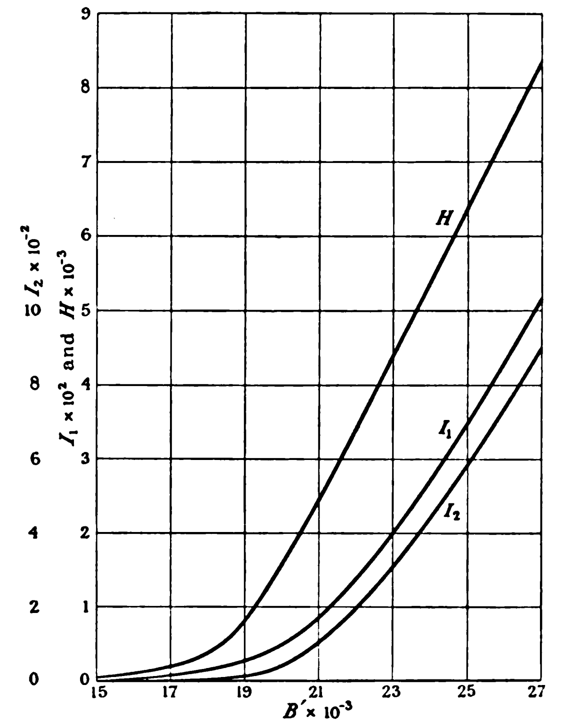

FIG. 14.

$$I_1 = \frac{10}{4\pi}\int \frac{H\,dB'}{(B')^2}$$

$$I_2 = \frac{10}{4\pi}\left\{\frac{H^2}{B'} - \int \frac{H\,dH}{B'}\right\}$$

straight line represented by equation (36) with the B', H curve of the laminated iron (see Fig. 13); and thus the limits of the integrals are obtained.

The coefficients of N and s within the brackets in equations (39) and (40) involve the laminated iron only, and can be computed once for all from the B', H curve. Fig. 14 gives the integrals in the form of curves, corresponding to the curve of Fig. 13. The upper part of the B, H curve on which the results are based is beyond the range of ordinary testing and is generally deduced from an extrapolation formula, making use of the established result * that the curve is asymptotic to the straight line

$$B = H + B_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

in which B_0 is a constant of about 21 000 lines per cm².

* Sir ROBERT HADFIELD and Prof. B. HOPKINSON: "The Magnetic Properties of Iron and its Alloys in Intense Fields," *Journal I.E.E.*, 1911, vol. 46, p. 235.

Kennelly's extrapolation formula is of the form

$$B = H + B_0 \frac{H}{H + H'} \quad . \quad . \quad . \quad . \quad (42)$$

in which H' is a constant, so chosen as to make the experimental and extrapolated curves join. In the author's experience, however, the junction is not made without a distinct kink, and he prefers the form, involving two disposable constants,

$$B = H + B_0 \frac{H + H_0}{H + H'} \quad . \quad . \quad . \quad . \quad (43)$$

By means of this the curves can be made to join in the same direction. The curve of Fig. 13 is extrapolated above $H = 100$ by means of the formula *

$$B = H + 20\,730 \frac{H + 25}{H + 46} \quad . \quad . \quad . \quad (44)$$

and the integrals of Fig. 14 have, except at the lower end, been deduced from this formula.

The magnetomotive force required for the gap is proportional to N, being $GN/(s + t)$, so the whole magnetomotive force from pole-face to armature core is determinate. These are sensibly equipotential regions, and it is convenient to treat the intervening region as a unit. It may be noted that, in the interpolar space, the potential of the armature core is brought to the crowns of the teeth, and thus affects the interpolar fringe flux. The effect of the saturation of the teeth on armature reaction is discussed later (Section 11).

(6) Fringe Flux at Pole-Tips.

The interpolar field in the case of a pair of rectangular poles, opposite in polarity, and separated by a uniform gap from a plane armature surface, was discussed in the I.E.E. paper cited on page 1117. The actual salient pole is not usually rectangular at the tip, nor is the corner sharp; but its angle is generally less than a right angle, and the corner is rounded off to accord with limitations of manufacture. The following solution is proposed as being more in accordance with actual conditions.†

Consider the transformation

$$z = \frac{\gamma}{(1-\lambda)\pi} \int \frac{(\zeta - a)d\zeta}{a\zeta(\zeta + 1)^{\frac{1}{2}}}$$
$$= \frac{\gamma}{(1-\lambda)\pi} \left\{ 2\frac{(\zeta+1)^{\frac{1}{2}}}{a} + \log \frac{(\zeta+1)^{\frac{1}{2}} + 1}{(\zeta+1)^{\frac{1}{2}} - 1} + j\pi \right\} \quad (45)$$

This converts the positive half-plane of ζ into the quarter plane of z, bounded, as shown in Fig. 15, by the positive axes of x and y, and by the two sides of the line $A\infty$. With the latter line at potential $1/(1-\lambda)$ and the axes of x and y at zero potential, the field is determined by

$$\phi + j\psi = \frac{1}{1-\lambda}\left[1 + \frac{j}{\pi}\log \zeta\right] \quad . \quad . \quad (46)$$

* Leading (with $\lambda = 0{\cdot}91$) to $B' = H + 18\,860\,(H + 25)/(H + 46)$.

† The results of this calculation were given by the author in the course of a discussion on a paper entitled "The Reluctance of Some Irregular Magnetic Fields," by John F. H. Douglas. See *Transactions of the American I.E.E.*, 1915, vol. 34, p. 1130.

If λ is given some value about $0{\cdot}2$ or $0{\cdot}3$, the line of unit potential bears a close resemblance, in the neighbourhood of the point A, to the contour of a section of a pole-tip; and the flux which reaches the armature in the interpolar space issues from this neighbourhood. It remains, therefore, to determine an appropriate value for the constant a; and to select, from the system of equipotential lines, that which most nearly resembles the required contour.

The following appears to be a reasonable method of

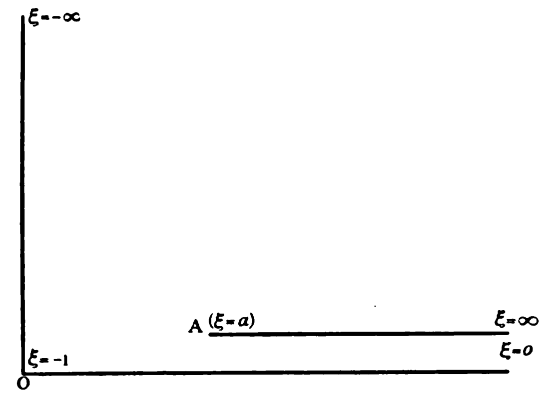

Fig. 15.—Plane of z.

making the selection. Let the origin in Fig. 15 be taken midway between the two poles when interpoles are absent, or at the nearer interpole tip when interpoles are present, since there is no appreciable drop of potential across the interpole face. Let the extreme limit of the equipotential surface selected to represent the pole, reckoned to the tangent normal to the armature face, be taken at the same distance from the origin as the extreme limit of the actual pole is from the interpole tip; and let the radius of curvature at the extreme limit be made the same as the radius of the actual pole-

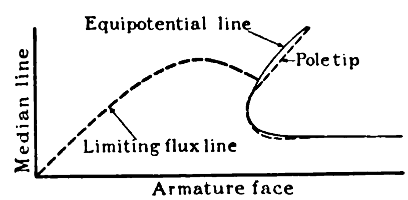

Fig. 16.

tip. The actual and assumed pole-tips in a typical case are shown in Fig. 16.

For the equipotential line at unit potential, equation (46) gives

$$\zeta = e^{(1-\lambda)\pi\psi + j\lambda\pi}$$
$$= qe^{j\lambda\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

and from equation (45)

$$\frac{dz}{dq} = \frac{\gamma}{(1-\lambda)\pi} \cdot \frac{qe^{j\lambda\pi} - a}{aq(qe^{j\lambda\pi} + 1)^{\frac{1}{2}}} \quad . \quad . \quad (48)$$

If ds is an element of the equipotential line and θ its slope,

$$dz = e^{j\theta} ds$$

Hence

$$\frac{ds}{dq} = \frac{\gamma}{(1-\lambda)\pi} \cdot \frac{[a^2 + q^2 - 2aq\cos\lambda\pi]^{\frac{1}{2}}}{q[1 + q^2 + 2q\cos\lambda\pi]^{\frac{1}{2}}} \quad . \quad (49)$$

$$\theta = \arc\tan\frac{q\sin\lambda\pi}{q\cos\lambda\pi - a} - \tfrac{1}{2}\arc\tan\frac{q\sin\lambda\pi}{q\cos\lambda\pi + 1} \quad (50)$$

$$\frac{d\theta}{dq} = -\sin\lambda\pi\left\{\frac{a}{a^2 + q^2 - 2aq\cos\lambda\pi} + \frac{1}{2(1 + q^2 + 2q\cos\lambda\pi)}\right\} \quad (51)$$

The radius of curvature $ds/d\theta$ is accordingly deducible from equations (49) and (51). At the extreme tip $\theta = \frac{1}{2}\pi$, and equation (50) gives

$$q^2 + 2q\cos\lambda\pi = a^2 + 2a$$

or $$q = (a^2 + 2a + \cos^2\lambda\pi)^{\frac{1}{2}} - \cos\lambda\pi \quad . \quad . \quad (52)$$

On the axis of x, representing the armature face, ϕ is zero, ζ lies between -1 and 0, and ψ lies between 0 and $-\infty$. Writing

$$\zeta = -e^{(1-\lambda)\pi\psi}$$

x is given by [see equation (45)]

$$x = \frac{\gamma}{(1-\lambda)\pi}\left\{\frac{2}{a}(1 - e^{(1-\lambda)\pi\psi})^{\frac{1}{2}} + 2\log\left[(1 - e^{(1-\lambda)\pi\psi})^{\frac{1}{2}} + 1\right] - (1-\lambda)\pi\psi\right\} \quad (53)$$

which, as ψ approaches $-\infty$, tends towards the value

$$x = \frac{\gamma}{(1-\lambda)\pi}\left\{\frac{2}{a} + \log 4\right\} - \gamma\psi \quad . \quad . \quad (54)$$

The total flux is accordingly the same as if the gap density extended over the whole armature face, with the exception of a distance, for each pole-tip, of

$$d = \frac{\gamma}{(1-\lambda)\pi}\left(\frac{2}{a} + \log 4\right) \quad . \quad . \quad . \quad (55)$$

For the purpose of determining the reluctance of the gap, the fringing is best expressed by the fraction of the length of the gap which must be added to the pole-face in a peripheral direction to give the same flux, if assumed at normal gap density throughout. It is accordingly the value of x/γ given by equations (45), (47) and (52), diminished by the value of d/γ given by equation (55). Values * of the fringing coefficient are given in Fig. 17.

It is, however, still necessary to determine an appropriate value for γ, the equivalent gap for the purpose, between pole-face and armature face, assumed plane. It has already been remarked that, in the interpolar space, the potential of the armature core appears at the tooth crowns, thus causing an increase in interpolar flux as the teeth under the pole become more saturated. It seems reasonable, accordingly, to assume as the value of γ the equivalent air-gap G as determined in Sections (3) and (4), plus the air equivalent of the teeth. This ensures continuity in the field between polar and interpolar spaces, and takes account of the ruling factors of the problem.

The strength of the field at the armature face is sometimes required and is readily found. Its value at the point determined, in terms of the parameter ψ, by equation (53) is

$$-\frac{d\psi}{dx} = \frac{a}{\gamma} \cdot \frac{(1 - e^{(1-\lambda)\pi\psi})^{\frac{1}{2}}}{a + e^{(1-\lambda)\pi\psi}} \quad . \quad . \quad . \quad (56)$$

Reviewing the problem in the light of the proposed solution, perhaps the most significant feature is that

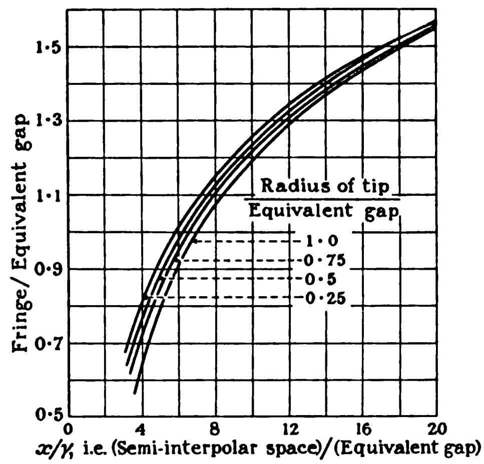

FIG. 17.

the precise form of the pole-tip, so that it be generally of the kind under consideration, has little effect on the total flux. This is clearly shown in Fig. 17. Even the differences indicated in this figure are probably exaggerated; for the assumed pole falls away sensibly from the actual pole before the tip radius is reached, as can be seen in Fig. 16, thus tending to reduce the

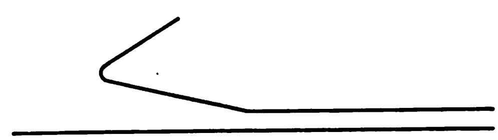

FIG. 18.

flux and to give too low a value for the coefficient. The reduction, moreover, is greater, the greater the value of λ, i.e. of the radius of the tip. Some such falling away of the pole-tip may, however, be taken as compensating for the falling away of the armature due to convexity. Accordingly, whilst the upper curves in Fig. 17 are probably in sensible agreement with the facts, the lower ones should be raised somewhat: and it is not unlikely that the highest curve of the figure fairly represents the facts, whatever the radius of the tip, within ordinary limits. The exact angle of the pole-tip is of small consequence, as very little of the flux issues from the flank beyond the radius. This is shown in Fig. 16, in which the limiting line of flux is indicated.

* The calculation involves a certain amount of cross-plotting; a note on the method used is given in Appendix 4.

In some machines the pole-tips are chamfered at a small angle, as in Fig. 18, in order to provide more gradual variation in the field. The determination of the fringe is thereby rendered more difficult. The field in the main gap rapidly approaches uniformity; and the field under the chamfer approaches a known limit, the lines of flux becoming ultimately arcs of circles. There are two regions, however, to which special consideration must be given, (1) the region of the beginning of the chamfer, and (2) the region of the pole-tip. Unless the chamfer is unduly short, these may be discussed separately.

The region of the beginning of the chamfer (Fig. 19) is not of very much consequence. At points remote from A the field in the main gap is uniform and equal to $1/\gamma$, that under the chamfer is sensibly equal to $1/(r\alpha + \gamma)$, where α is the angle of chamfer and r the distance from the point A. It will be convenient to treat these fields as extending to the point A, where they are continuous, and the disturbance as a correction to be applied to this assumed field.

If $n = \alpha/\pi$, the transformation

$$z = -\frac{\gamma}{\pi}\int\frac{(1-\zeta)^n}{\zeta}d\zeta \quad . \quad . \quad . \quad . \quad (57)$$

represents the gap of Fig. 19. With the pole at unity

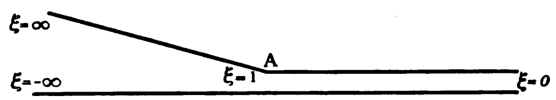

FIG. 19.

potential and the armature at zero potential, the field is determined in terms of ζ by

$$\chi = \phi + j\psi = 1 + \frac{j}{\pi}\log\zeta \quad . \quad . \quad . \quad (58)$$

and in terms of z by

$$z = j\gamma\int[1 - e^{-j\pi(\chi-1)}]^n d\chi \quad . \quad . \quad . \quad (59)$$

At the pole-face this reduces to

$$z = -\gamma\int(1 - e^{\pi\psi})^n d\psi \quad . \quad . \quad . \quad . \quad (60)$$

When $\psi < 0$ this may be written

$$z = -\gamma\int\Big[1 - ne^{\pi\psi} - \frac{n(1-n)}{2!}e^{2\pi\psi} - \frac{n(1-n)(2-n)}{3!}e^{3\pi\psi} + \ldots\Big]d\psi$$

$$= -\gamma\Big\{\psi - \frac{n}{\pi}\Big[e^{\pi\psi} + \frac{1-n}{2^2}e^{2\pi\psi} + \frac{(1-n)(1-\frac{1}{2}n)}{3^2}{}_{3\pi\psi} + \ldots\Big]\Big\} \quad (61)$$

This series is convergent as long as $\psi \ngtr 0$. Hence taking the origin at A ($\psi = 0$), when $e^{\pi\psi}/\psi$ has become small

$$x = -\gamma\Big[\psi_1 + \frac{n}{\pi}S_1\Big] \quad . \quad . \quad . \quad . \quad (62)$$

where

$$S_1 = 1 + \frac{1-n}{2^2} + \frac{(1-n)(1-\frac{1}{2}n)}{3^2} + \ldots \quad . \quad (63)$$

When $\psi > 0$, equation (60) may be written in the form

$$z = -\gamma e^{-j\alpha}\int e^{n\pi\psi}(1 - e^{-\pi\psi})^n d\psi$$

$$= -\gamma e^{-j\alpha}\int\Big[e^{n\pi\psi} - ne^{-(1-n)\pi\psi} - \frac{n(1-n)}{2!}e^{-(2-n)\pi\psi}\ldots\Big]d\psi$$

$$= -\gamma e^{-j\alpha}\Big\{\frac{e^{n\pi\psi}}{n\pi} + \frac{n}{\pi}\Big[\frac{e^{-(1-n)\pi\psi}}{1-n} + \frac{1-n}{2^2(1-\frac{1}{2}n)}e^{-(2-n)\pi\psi} + \ldots\Big]\Big\} \quad (64)$$

The series is convergent as long as $\psi \nless 0$; hence, when ψ is large

$$z = -\gamma e^{-j\alpha}\Big\{\frac{e^{n\pi\psi_2} - 1}{n\pi} - \frac{n}{\pi}S_2\Big\} \quad . \quad . \quad (65)$$

where

$$S_2 = \frac{1}{1-n} + \frac{1-n}{2^2(1-\frac{1}{2}n)} + \frac{(1-n)(1-\frac{1}{2}n)}{3^2(1-\frac{1}{3}n)} + \ldots \quad (66)$$

z may be written

$$z = re^{j(\pi-\alpha)} = -re^{-j\alpha} \quad . \quad . \quad . \quad (67)$$

and equation (65) gives

$$\psi_2 = \frac{1}{\alpha}\log\Big[\frac{r\alpha}{\gamma} + 1 + n^2S_2\Big] \quad . \quad . \quad (68)$$

The total flux from $z = -re^{-j\alpha}$ to $z = x$ is accordingly

$$\psi_2 - \psi_1 = \frac{1}{\alpha}\log\Big(\frac{r}{\gamma} + 1 + n^2S_2\Big) + \frac{x}{\gamma} + \frac{n}{\pi}S_1 \quad (69)$$

The distribution of flux assumed provisionally accounts for an amount $\frac{1}{\alpha}\log\Big(\frac{r\alpha}{\gamma} + 1\Big) + \frac{x}{\gamma}$, and the correction to be applied to this is therefore S_1n/π or $S_1\alpha/\pi^2$. S_1 is somewhat short of $\pi^2/6$ and the correction is nearly $\alpha/6$, this being an addition to the permeance of the gap per unit axial length.

The effect of this part of the chamfer on the distribution of flux at the armature face will now be given for what it is worth. The deviation from the assumed distribution is not very great, although much greater than might be surmised from the insignificance of its integral effect.

At the armature face, $\zeta = -e^{\pi\psi}$ and the point corresponding to $\psi = 0$ is to the left of the axis of y. Write accordingly

$$x = -c - \gamma\int^{\psi}(1 + e^{\pi\psi})^n d\psi \quad . \quad . \quad . \quad (70)$$

in which c has to be determined. When $\psi < 0$

$$x = -c - \gamma\Big\{\psi + \frac{n}{\pi}\Big[e^{\pi\psi} - \frac{1-ne_{2\pi\psi}}{2^2} + \frac{(1-n)(1-\frac{1}{2}n)}{3^2}e^{3\pi\psi}\ldots\Big] - \frac{n}{\pi}S_1'\Big\} \quad (71)$$

where $S_1' = 1 - \frac{1-n}{2^2} + \frac{(1-n)(1-\frac{1}{2}n)}{3^2}$. (72)

When $e^{\pi\psi}/\psi$ is small this reduces to

$$x = -c - \gamma\psi + \frac{n}{\pi}\gamma S_1' \quad . \quad . \quad . \quad (73)$$

Equating this to the value of x given in equation (62), since the lines of flux are here straight and normal to armature and pole-faces,

$$\begin{aligned} c &= \frac{n}{\pi}\gamma(S_1 + S_1') \\ &= 2\frac{a}{\pi^2}\gamma\left(1 + \frac{(1-n)(1-\frac{1}{2}n)}{3^2} + \ldots\right) \\ &= \tfrac{1}{4}a\gamma \text{ approximately} \quad . \quad . \quad . \quad . \quad . \quad . \quad (74) \end{aligned}$$

Equation (71) determines x when ψ lies between $-\infty$ and 0. When $\psi > 0$, x is given by

$$x = -c - \gamma e^{n\pi\psi}\left\{\frac{1}{n\pi} - \frac{n}{\pi}\left[\frac{e^{-\pi\psi}}{1-n} - \frac{1-n}{(1-\frac{1}{2}n)2^2}e^{-2\pi\psi} + \ldots\right]\right\} + \gamma\left\{\frac{1}{n\pi} - \frac{n}{\pi}S_2'\right\} \quad (75)$$

where

$$S_2' = \frac{1}{1-n} - \frac{1-n}{2^2(1-\frac{1}{2}n)} + \frac{(1-n)(1-\frac{1}{2}n)}{3^2(1-\frac{1}{3}n)} \quad (76)$$

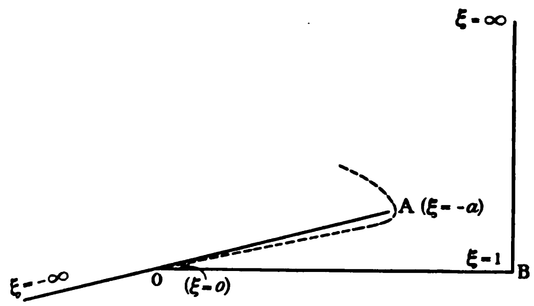

FIG. 20.

The flux density at the armature face is given in terms of the parameter ψ by

$$-\frac{d\psi}{dx} = \frac{1}{\gamma(1 + e^{\pi\psi})^n} \quad . \quad . \quad . \quad . \quad (77)$$

The field about the tip of the chamfered pole may be deduced by means of the transformation

$$z = Kb\int_0^{\zeta} \frac{(\zeta + a)\zeta^n}{\zeta(1-\zeta)^{\frac{1}{2}}}d\zeta \quad . \quad . \quad . \quad (78)$$

in which K is a constant to be determined, b represents the distance OB in Fig. 20, and n is now $a/(1-\lambda)\pi$, a being the angle of chamfer and λ having the same significance as in the fringing problem for uniform gap. This transformation converts the half-plane of ζ into the figure in the plane of z, bounded, as shown in Fig. 20, by the armature face OB, the median line at right angles thereto, the lower side of the line OA and its upper side throughout its length. If OA is at potential $1/(1-\lambda)$ and OB, with the median line, at zero potential, λ and a can be so chosen that the equipotential line of potential unity is similar in the neighbourhood of the tip, to the actual pole, as shown in broken lines.

It is not necessary for the present purpose to consider the case in which the modulus of ζ is greater than unity. The expression in equation (78) can accordingly be expanded and integrated term by term, giving

$$\begin{aligned} z &= Kb\left\{\frac{\zeta^{1+n}}{1+n} + \frac{1}{2}\frac{\zeta^{2+n}}{2+n} + \frac{\frac{1}{2}\cdot\frac{3}{2}}{2\,!}\frac{\zeta^{3+n}}{3+n} + \ldots + a\left[\frac{\zeta^n}{n} + \frac{1}{2}\frac{\zeta^{1+n}}{1+n} + \frac{\frac{1}{2}\cdot\frac{3}{2}}{2\,!}\frac{\zeta^{2+n}}{2+n} + \ldots\right]\right\} \\ &= Kb\zeta^n\left\{S_1(\zeta) - nS_2(\zeta) + n^2S_2(\zeta) \ldots + a\left[\frac{1}{n} + \tfrac{1}{2}(S_2'(\zeta) - nS_3'(\zeta) + \ldots)\right]\right\} \quad (79) \end{aligned}$$

in which $S_r(\zeta) = \zeta + \frac{1}{2}\cdot\frac{\zeta^2}{2^r} + \frac{\frac{1}{2}\cdot\frac{3}{2}}{2\,!}\cdot\frac{\zeta^3}{3^r} + \ldots \quad . \quad (80)$

$$S_r'(\zeta) = \zeta + \frac{3}{2}\cdot\frac{\zeta^2}{2^r} + \frac{\frac{3}{2}\cdot\frac{5}{2}}{2\,!}\cdot\frac{\zeta^3}{3^r} + \ldots * \quad (81)$$

The series $S_1S_2\ldots$ and $S_2'S_3'\ldots$ are convergent as long as mod. $\zeta \not> 1$. When $\zeta = 1$, $z = b$, and K is accordingly given by

$$1 = K\left\{S_1(1) - nS_2(1) + n^2S_3(1) \ldots + a\left[\frac{1}{n} + \tfrac{1}{2}(S_2'(1) - nS_3'(1) + n^2S_4'(1)\ldots)\right]\right\}\dagger \quad (82)$$

It may be noted that n is rarely as great as $0{\cdot}1$, and a few terms of the series give sufficient accuracy.

The field is determined by

$$\phi + j\psi = -\frac{j}{(1-\lambda)\pi}\log\zeta \quad . \quad . \quad . \quad (83)$$

and on the equipotential $\phi = 1$

$$\begin{aligned} \zeta &= e^{-(1-\lambda)\pi\psi + (1-\lambda)\pi j} \\ &= qe^{(1-\lambda)\pi j} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (84) \end{aligned}$$

Proceeding as before, on the equipotential $\phi = 1$

$$\frac{dz}{dq} = Kb\frac{(qe^{(1-\lambda)\pi j} + a)q^n e^{ja}}{q(1 - qe^{(1-\lambda)\pi j})} \quad . \quad . \quad . \quad (85)$$

whence $\quad \dfrac{ds}{dq} = Kb\dfrac{(q^2 + a^2 - 2qa\cos\lambda\pi)^{\frac{1}{2}}q^n}{q(q^2 + 1 + 2q\cos\lambda\pi)^{\frac{1}{4}}} \quad . \quad . \quad (86)$

$$\theta = \arc\tan\frac{q\sin\lambda\pi}{a - q\cos\lambda\pi} + \tfrac{1}{2}\arc\tan\frac{q\sin\lambda\pi}{1 + q\cos\lambda\pi} + a \, . \quad (87)$$

At the extreme tip, $\theta = \frac{1}{2}\pi + a$, and q is given by the equation [cf. equation (52)]

$$q = \sqrt{(a^2 + 2a + \cos^2\lambda\pi)} - \cos\lambda\pi \quad . \quad (88)$$

The radius of curvature at the extreme tip could be deduced exactly as in the problem of the uniform gap, and with little greater labour. It was shown, however,

* Note that

$S_1(\zeta) = 2[1 - (1-\zeta)^{\frac{1}{2}}]$; $S_2(\zeta) = 4[\log\frac{1}{2}[1 + (1-\zeta)^{\frac{1}{2}}] + 1 - (1-\zeta)^{\frac{1}{2}}]$;

$S_2'(\zeta) = -4\log\frac{1}{2}[1 + (1-\zeta)^{\frac{1}{2}}]$

† Note that: $S_1(1) = 2$; $S_2(1) = 1{\cdot}228$; $S_3(1) = 1{\cdot}087$; $S_4(1) = 1{\cdot}04$; $S_5(1) = 1{\cdot}02$; $S_6(1) = 1{\cdot}0$; $S_2'(1) = 2{\cdot}772$; $S_3'(1) = 1{\cdot}366$; $S_4'(1) = 1{\cdot}135$; ; $= 1{\cdot}04$; $S_6(1 = 1{\cdot}0$.

in discussing the results of this case, that they were not greatly affected by the radius of the tip, and for the purpose in view it is sufficient to work with a constant value of λ.

At the armature face [see equation (83)]

$$\zeta = e^{-(1-\lambda)\pi\psi} \quad . \quad . \quad . \quad . \quad (89)$$

If now x_1 is the value of z corresponding to a large value ψ_1,

$$x_1 = \frac{Kbae^{-n(1-\lambda)\pi\psi_1}}{n}$$

or

$$\psi_1 = \frac{1}{a}\left[\log\frac{Kba}{n} - \log x_1\right] \quad . \quad . \quad (90)$$

At the point B, $\psi = 0$, and thus ψ_1 is the total flux entering the armature between $x = x_1$ and $x = b$. If the normal field of the chamfer were extended indefinitely, the flux entering the armature between x_1 and x_2 would be

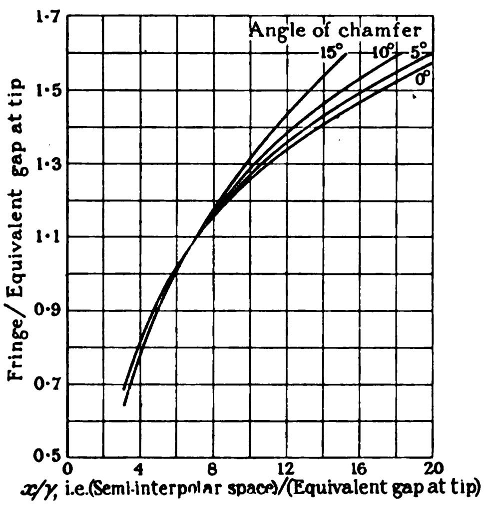

FIG. 21.

$$\psi_1 - \psi_2 = \frac{1}{a}[\log x_2 - \log x_1] \quad . \quad . \quad (91)$$

Accordingly the extent of normal chamfer field giving the same flux to the armature as the actual pole-tip is determined by

$$x_2 = \frac{Kba}{n} \quad . \quad . \quad . \quad . \quad . \quad . \quad (92)$$

Equations (79), (84) and (88) determine z at the extreme tip, and the modulus $\bar{z}$ of this is the distance of the tip from 0. The addition for the fringing is therefore

$$\frac{Kba}{n} - \bar{z} \quad . \quad . \quad . \quad . \quad . \quad . \quad (93)$$

The gap at the tip is $\bar{z}\sin\alpha$, and the distance of the tip from the median line, $b - \bar{z}\cos\alpha$. Fig. 21 gives values of $[Kban^{-1} - \bar{z}]/\bar{z}\sin\alpha$ plotted against $[b - \bar{z}\cos\alpha]/\bar{z}\sin\alpha$, for values of α, 0°, 5°, 10°, 15°. In computing these curves, λ was taken constant, at value $\frac{2}{3}$.* In using the curves, if g is the minimum, G the equivalent gap in the centre portion of the pole, ϵ the air equivalent of the teeth, the gap at the tip may be taken as the minimum gap at this place, plus $G - g + \epsilon$.

* It should be noted that the gap at the top of a chamfered pole is large, so that the fraction (radius of tip)/gap is correspondingly small.

The distribution of flux at the armature face can now be readily computed. The position of the point determined by ψ is given by equation (79), in which ζ is given by equation (89). The flux density at the point is

$$-\frac{d\psi}{dx} = \frac{e^{a\psi}[1 - e^{-(1-\lambda)\pi\psi}]^{\frac{1}{2}}}{(1-\lambda)\pi Kb[e^{-(1-\lambda)\pi\psi} + a]} \quad . \quad . \quad (94)$$

(7) FRINGE FLUX AT END OF CORE.

The fringes between the pole-ends and armature core are not susceptible to satisfactory determination by present methods, for two reasons; first, because the problem, if the armature teeth are taken into account, is three-dimensional; and secondly, because the flux is not entirely local or naturally delimited. With regard to the first, it is necessary to assume a uniform gap which, it is intended, shall have substantially the same effective fringe as the actual gap. For this purpose the gap used in the last Section is suggested, viz. the equivalent air-gap plus the air equivalent of the teeth, although for most purposes of design the last factor may be omitted. This assumption, if not correct, at least depends on the ruling factors and serves the purpose of a secondary calculation. With regard to the second difficulty, the problem on which the results are based involves an infinite fringe, although agreeing with actual conditions in the vicinity of the gap. It is accordingly a matter of judgment how much of the computed fringe should be taken as effective; but it is evidently something less in extent than the end connections of the armature winding.

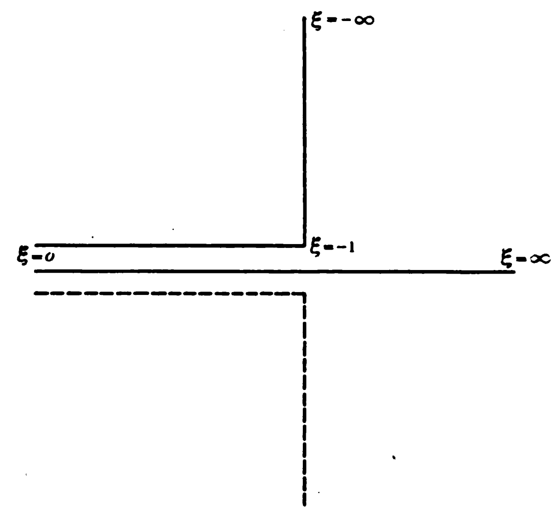

FIG. 22.

The transformation is

$$z = \frac{\gamma}{2\pi}\int\frac{(\zeta+1)^{\frac{1}{2}}}{\zeta}d\zeta$$
$$= \frac{\gamma}{2\pi}\left\{2(\zeta+1)^{\frac{1}{2}} - \log\frac{(\zeta+1)^{\frac{1}{2}}+1}{(\zeta+1)^{\frac{1}{2}}-1}\right\} \quad . \quad (95)$$

which converts the half-plane of ζ into a system in the plane of z bounded as shown in full lines in Fig. 22. The system is taken as being symmetrical about the middle line of the gap. The field is given by

$$\phi + j\psi = -\frac{j}{2\pi}\log\zeta \quad . \quad . \quad . \quad (96)$$

The relation between ψ and x is accordingly

$$x=\frac{\gamma}{2\pi}\{2(e^{-2\pi\psi}+1)^{\frac{1}{2}}-2\log[(e^{-2\pi\psi}+1)^{\frac{1}{2}}+1]-2\pi\psi\} \quad (97)$$

When ψ is large and positive this equation reduces to

$$\psi + \frac{x}{\gamma} = \frac{1}{\pi}(1 - \log 2) \quad . \quad . \quad . \quad (98)$$

If ψ' is the value given by equation (97) when x

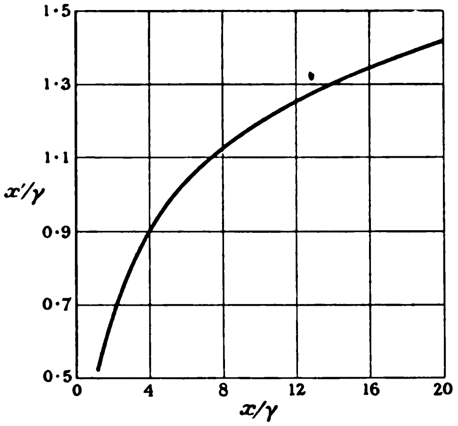

FIG. 23.

corresponds to the adjudged limit of the effective fringe, and if x' is defined by

$$\frac{x' - x}{\gamma} = \psi - \psi'$$

or

$$x' = \gamma\left\{\frac{1}{\pi}(1 - \log 2) - \psi'\right\} \quad . \quad . \quad (99)$$

then x' may be taken as representing the fringe, being the extension of the pole-face required to give the same total flux, normal density being assumed throughout. Fig. 23 gives this fringe as a function of the adjudged limit of effective fringe.

(8) Radial Ducts.

The effect of introducing a radial duct in armature core or pole-piece is to reduce the equivalent area of the pole-face, the reduction being found by annulling a certain fraction of the width of the duct, given by equation (8) or Fig. 3, in which, however, s is now the width of the duct, and g an equivalent gap. Where there are ducts in both members, opposite to one another, the appropriate reduction is given by equation (27). The solution is not perfect, since the problem is really a three-dimensional one when slots are present. The value of g is greater than the minimum gap, and may be taken as G, the equivalent gap of the slotted surface.

(9) Band Recesses.

Many armatures have their windings held in by means of binding bands, composed generally of steel

FIG. 24.

wire or strip, but sometimes of phosphor-bronze. The bands lie in recesses in the core surface (Fig. 24) and are separated from the laminations by an insulating layer, causing a local variation in the reluctance of the

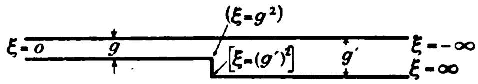

FIG. 25.

gap, which can be expressed as a variation in its equivalent area. The problem is again a three-dimensional one which has to be treated as two-dimensional, and two cases arise according as the band is magnetic or non-magnetic.

The case of a non-magnetic band may be deduced from consideration of a gap varying suddenly as shown

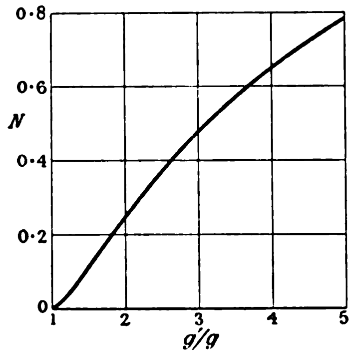

FIG. 26.

in Fig. 25. The appropriate transformation from the half-plane of ζ is

$$z = \frac{g'}{\pi}\int\left[\frac{\zeta - g^2}{\zeta - g'^2}\right]^{\frac{1}{2}}\frac{d\zeta}{\zeta}$$

$$= \frac{1}{\pi}\left\{g' \operatorname{arc\,cosh}\frac{2\zeta - (g'^2 + g^2)}{g'^2 - g^2}\right.$$

$$\left. - g \operatorname{arc\,cosh}\frac{(g'^2 + g^2)\zeta - 2g'^2g^2}{(g'^2 - g^2)\zeta}\right\} \quad (100)$$

The field is given by

$$\phi + j\psi = -\frac{j}{\pi}\log\zeta \quad . \quad . \quad . \quad (101)$$

When ζ is large, real and positive,

$$x_2 = \frac{1}{\pi}\left\{g'\left[-\pi\psi_2 - \log\frac{g'^2 - g^2}{4}\right] - g \operatorname{arc\,cosh}\frac{g'^2 + g^2}{g'^2 - g^2}\right\}$$

When ζ is small, real and positive,

$$x_1=\frac{1}{\pi}\left\{g' \operatorname{arc\,cosh} \frac{g'^2+g^2}{g'^2-g^2}-g\left[\pi\psi_1+\log \frac{4g^2g'^2}{g'^2-g^2}\right]\right\}$$

Whence

$$\psi_1-\psi_2=\frac{x_2}{g'}+\frac{-x_1}{g}+\frac{1}{\pi}\left\{\log \frac{(g'^2-g^2)^2}{16g^2g'^2}\right.$$
$$\left.+\left(\frac{g}{g'}+\frac{g'}{g}\right) \operatorname{arc\,cosh} \frac{g'^2+g^2}{g'^2-g^2}\right\} \quad (102)$$

Thus the flux, in excess of that required to fill both gaps, each at its appropriate density, is *

$$N=\frac{1}{\pi}\left\{2 \log\left[\tfrac{1}{4}\left(\frac{g'}{g}-\frac{g}{g'}\right)\right]+\left(\frac{g'}{g}+\frac{g}{g'}\right) \operatorname{arc\,cosh} \frac{g'^2+g^2}{g'^2-g^2}\right\}$$
$$=\frac{1}{\pi}\left\{2 \log\left[\tfrac{1}{4}\left(\frac{g'}{g}-\frac{g}{g'}\right)\right]+\left(\frac{g'}{g}+\frac{g}{g'}\right) \log \frac{g'+g}{g'-g}\right\} \quad (103)$$

Fig. 26 gives N as a function of g'/g (see also Fig. 42).

If b is the width of the band recess, and x the fraction of this which should be annulled to give an equivalent area of normal gap,

$$\frac{b}{g'}+2N=\frac{b}{g}(1-x)$$

or

$$x=1-\frac{g}{g'}-2N\frac{g}{b} \quad . \quad . \quad . \quad (104)$$

When steel bands are used the problem is different, for although iron is removed from the crowns of the

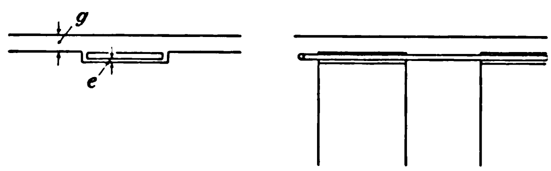

FIG. 27.

teeth, the magnetic band, carried over teeth and slots (see Fig. 27), tends to counteract the increase of reluctance caused by the removal. The band may be regarded as an equipotential region, at some potential (v) between that of the pole (unity) and that of the armature core (zero).

Let b be the breadth of the band space and $(1-x)b$ the equivalent breadth. Let g be the gap between pole-face and band, and e the gap between band and armature core (see Fig. 27), then †

$$\frac{s+t}{g}(1-v)=\frac{t}{e}v=\frac{(1-x)(s+t)}{G}=\frac{(s+t)t}{tg+(s+t)e}$$

or

$$x=\frac{(s+t)e-(G-g)t}{tg+(s+t)e} \quad . \quad . \quad . \quad (105)$$

This is the fraction of the breadth of the band recess to be subtracted from the core length, in order to allow for its presence, the remainder being treated as normal gap. The correction in this case is a small one, and, with certain dimensions, may conceivably be negative.

* The expression for N was originally deduced by the author in 1909 in connection with the problem of the reactance of a conductor imbedded in a semi-closed slot (see section 12). The same mathematical problem, however, is involved in determining the resistance of a strip of uniform material, shaped like Fig. 25, and the result (103) was given in this connection by Dr. C. H. Lees (*Philosophical Magazine*, 1908, ser. 6, vol. 16, p. 734). The problem of the stepped gap has been discussed by Prof. W. Cramp and Miss N. I. Calderwood (see *Journal I.E.E.*, 1923, vol. 61, p. 1068).

† Certain small fringes are here neglected.

(10) DISTRIBUTED EXCITATION.

Hitherto the discussion has been confined to problems of uniform magnetomotive force; but in certain classes of machine the exciting winding is distributed in slots in the pole-face, so that the magnetomotive force is graduated. The problem of a rectangular slot in which a conductor conveying a current is located, and which is opposed by a plane equipotential surface, is the same as that of a pair of rectangular poles of opposite polarity opposed by a plane armature surface. The latter problem was discussed in the I.E.E. paper cited on page 1117. The transformation used is essentially the same as that of a slot in one of a pair of opposing equipotential surfaces (see Section 3), but the source of the flux is differently located. The two solutions are in fact additive, and both sources may be present in any strengths. The field at any point due to a winding distributed in slots is therefore readily determined: in fact the total flux from the centre of one tooth to the centre of the next is the same as if no current were carried in the slot separating them.

If, in Fig. 2, u is the magnetomotive force due to the current in the slot, and v that due to the other agents creating a potential difference between the two sides of the gap, z being connected with ζ by equation (11), the flux function may be written

$$\psi=\frac{u}{\pi}\log(\zeta+1)+\frac{v}{\pi}\log\zeta \quad . \quad . \quad (106)$$

and the force at the unslotted face is

$$F=\frac{u\zeta+v(\zeta+1)}{g[(\zeta+\lambda)(\zeta+\lambda^{-1})]^{\frac{1}{2}}} \quad . \quad . \quad (107)$$

in which ζ is real and positive, and λ is given by equation (12). The variation in the field through which the armature conductors pass can accordingly be determined.

(11) LOADED MACHINES.

When a machine is under load, the field due to the load is added to the exciting field. Unless the machine is of the compensated type, the resultant excitation varies from tooth to tooth, presenting the same problem as was considered in the preceding Section. When the load is so disposed as to have a component in the direction of the axis of excitation, it reacts on this, in effect increasing or diminishing it. But even when the axis of the load is in quadrature with the axis of excitation, as in d.c. machines having brushes at the neutral point, there is an effect due to the saturation of the teeth which is usually, though with little reason, provided against by assuming a certain percentage of the armature ampere-turns to react on the field.

The excitation required for gap and teeth, for any specified mean flux density in the gap, can be readily determined by the methods already discussed; and it is of no consequence whether the excitation is due to outside agency or to the load itself. The form of the

curve of magnetization for gap and teeth is, for a particular machine, shown in Fig. 28; and from this the mean flux density at any point in the gap of the loaded machine can be found. In the important case of d.c. machines having no compensating or other windings in the pole-face, the excitation varies by equal steps from tooth to tooth; and the mean excitation accordingly varies uniformly with the tangential* distance. A section of the curve of Fig. 28, comprised between certain determinate points P and Q, therefore represents, to some scale of abscissa, the mean distribution of flux along the air-gap in a tangential direction. The mean abscissa ON of the section, or that corresponding to the middle of the pole-face, represents the imposed excitation, including the component, if any, of armature ampere-turns in the direction of the axis of excitation. The mean ordinate MR of the section is the effective mean flux density, and the defect MN of

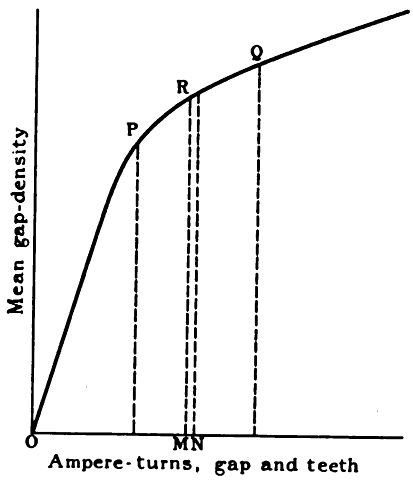

FIG. 28.

the corresponding abscissa from the mean abscissa represents the effect of saturation in causing a diminution of effective excitation. Expressed in the usual manner, as a percentage of the armature reaction, the effect is negligibly small at low saturation, rises to a maximum when the section includes the knee of the curve, and falls again to a low value when the teeth become saturated. The effects are noticeable in the speed curves of railway motors having a light exciting field.

The additional excitation due to the load has the effect of increasing the iron loss in the teeth, as compared with the light-load loss at the same speed and external excitation, the increase being of the nature of a load loss.

(12) Reactance of Conductors Embedded in Slots.

Hitherto the slot has been considered with regard to its effect on the field in the gap: the present Section deals with the flux-linkage of the current carried by the slot-embedded conductors, and is therefore concerned with the field in the slot itself, as well as that in the gap. In this discussion the form of the slot becomes a matter of importance.

When a current-carrying conductor is located in a rectangular slot, the field due to the current is small below the conductor, and becomes sensibly uniform at a short distance above the conductor. Fig. 29 shows a portion of the field due to an element of such a conductor. For the windings with which the engineer has

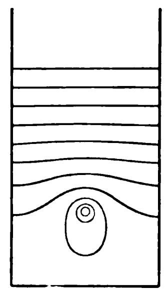

FIG. 29.

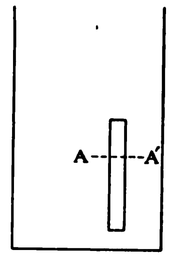

FIG. 30.

occasion to deal, it is generally sufficient to assume the field uniform above the conductors, until the neighbourhood of the mouth of the slot is reached; and further, when the current is distributed sensibly uniformly over a rectangular area as in Fig. 30, having two of its sides parallel to those of the slot, to assume that the flux-linkage is the same as if the current were

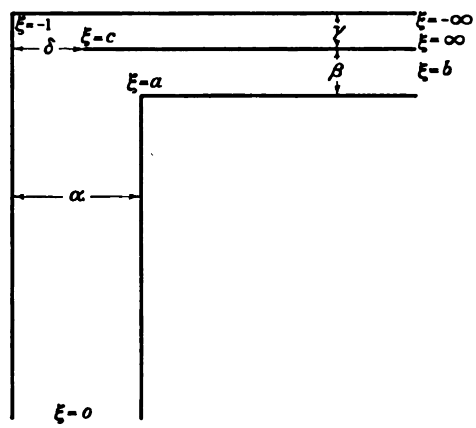

FIG. 31.

concentrated in a horizontal layer AA′ situated two-thirds of the height of the rectangle, measured from the bottom.* The present investigation is accordingly narrowed to that of the field about the mouth of the slot, with given difference of potential between the sides of the slot.

The case of a simple rectangular slot could readily be deduced from formulæ already given; but it is convenient here to treat this as a particular case of a more general problem.

* The principal directions in a dynamo may be referred to as: "radial," "axial," and "tangential."

* Where the rectangle is formed of a single conductor, the field itself tends to destroy the uniformity of the current, increasing its density towards the top. See A. B. Field: "Eddy Currents in Large Slot-wound Conductors," *Transactions of the American I.E.E.*, 1905, vol. 24, p. 761.

The transformation

$$z=\frac{\gamma}{\pi}\int\frac{(\zeta-c)\,(\zeta-a)^{\frac{1}{2}}}{\zeta(\zeta-b)\,(\zeta+1)^{\frac{1}{2}}}d\zeta$$
$$=\frac{1}{\pi}\left\{\gamma\operatorname{arc\,cosh}\frac{2\zeta+1-a}{1+a}+\alpha\operatorname{arc\,cos}\frac{(1-a)\zeta-2a}{(1+a)\zeta}\right.$$
$$\left.+\beta\operatorname{arc\,cosh}\frac{2(1+b)\,(b-a)+(1+2b-a)(\zeta-b)}{(1+a)\,(\zeta-b)}\right\}\quad(108)$$

in which a, b, c, are positive and in ascending order of magnitude, converts the half-plane of ζ into the plane of z bounded as shown in Fig. 31. In this equation

$$\frac{c}{b}a^{\frac{1}{2}}=\frac{\alpha}{\gamma}\quad.\;.\;.\;.\;.\;.\quad(109)$$

$$\frac{c-b}{b}\left(\frac{b-a}{1+b}\right)^{\frac{1}{2}}=\frac{\beta}{\gamma}\quad.\;.\;.\quad(110)$$

$$\delta=\frac{1}{\pi}\left\{\gamma\operatorname{arc\,cosh}\frac{2c+1-a}{1+a}+\alpha\operatorname{arc\,cos}\frac{(1-a)c-2a}{(1+a)c}\right.$$
$$\left.+\beta\operatorname{arc\,cosh}\frac{2(1+b)\,(b-a)+(1+2b-a)\,(c-b)}{(1+a)\,(c-b)}\right\}\quad(111)$$

For field write

$$\phi+j\psi=\tfrac{1}{2}\left(1+\frac{j}{\pi}\log\zeta\right)\quad.\;.\;.\quad(112)$$

which, when ζ is real and positive gives :—

$$\zeta=e^{2\pi\psi}\quad.\;.\;.\;.\;.\;.\quad(113)$$

When ζ is large, real and positive, equation (108) becomes

$$x=\frac{1}{\pi}\left\{\gamma\left[2\pi\psi_2-\log\frac{1+a}{4}\right]+\alpha\operatorname{arc\,cos}\frac{1-a}{1+a}\right.$$
$$\left.+\beta\operatorname{arc\,cosh}\frac{1+2b-a}{1+a}\right\}$$

When ζ is small, real and positive, equation (108) gives

$$y=-\frac{1}{\pi}\left\{-\gamma\operatorname{arc\,cos}\frac{1-a}{1+a}+\alpha\left[-2\pi\psi_1-\log\frac{1+a}{4a}\right]\right.$$
$$\left.+\beta\operatorname{arc\,cos}\frac{2a-b(1-a)}{b(1+a)}\right\}$$

whence

$$\psi_2-\psi_1=\tfrac{1}{2}\left\{\frac{x-\delta}{\gamma}+\frac{-y}{\alpha}+\frac{\delta}{\gamma}+\frac{1}{\pi}\log\frac{(1+a)^2}{16a}\right.$$
$$-\frac{1}{\pi}\left[\left(\frac{\alpha}{\gamma}-\frac{\gamma}{\alpha}\right)\operatorname{arc\,cos}\frac{1-a}{1+a}\right.$$
$$+\frac{\beta}{\gamma}\operatorname{arc\,cosh}\frac{1+2b-a}{1+a}$$
$$\left.\left.+\frac{\beta}{\alpha}\operatorname{arc\,cos}\frac{2a-b(1-a)}{b(1+a)}\right]\right\}\quad(114)$$

The flux may accordingly be computed by assuming that the gap is filled to the edge of the slot opening with a uniform field of appropriate density $1/(2\gamma)$ on one side and $-1/(2\gamma)$ on the other, that the slot is filled with appropriate uniform field $1/(2\alpha)$, and that there is, in addition, an amount of flux per unit length of core per unit difference of potential between the sides of the slot, given by

$$N=\frac{\delta}{2\gamma}+\frac{1}{\pi}\log\frac{1+a}{4\sqrt{a}}$$
$$-\frac{1}{2\pi}\left\{\left(\frac{\alpha}{\gamma}-\frac{\gamma}{\alpha}\right)\operatorname{arc\,cos}\frac{1-a}{1+a}\right.$$
$$+\frac{\beta}{\gamma}\operatorname{arc\,cosh}\frac{1+2b-a}{1+a}$$
$$\left.+\frac{\beta}{\alpha}\operatorname{arc\,cos}\frac{2a-b(1-a)}{b(1+a)}\right\}\quad(115)$$

In the more general case in which the slot is bounded by some equipotential of the field, the expression for

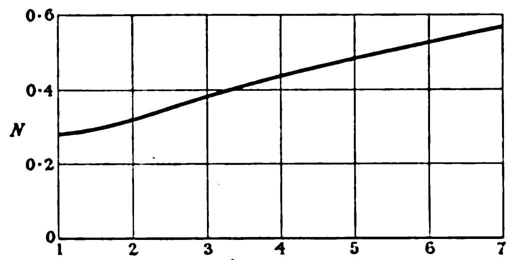

FIG. 32.

N is divided by $1-\lambda$ as in Section 6. If $p=a^{\frac{1}{2}}$ the general expression for N may be written [see equations (109) and (110)]

$$N=\frac{1}{1-\lambda}\left\{\frac{\delta}{2\gamma}+\frac{1}{\pi}\log\left[\tfrac{1}{4}(p+p^{-1})\right]\right.$$
$$-\frac{1}{\pi}\left[\left(\frac{\alpha}{\gamma}-\frac{\gamma}{\alpha}\right)\operatorname{arc\,tan}p+\frac{\beta}{\gamma}\operatorname{arc\,tanh}\frac{\beta p}{\alpha-\gamma p}\right.$$
$$\left.\left.+\frac{\beta}{\alpha}\operatorname{arc\,tan}\frac{\beta}{\alpha-\gamma p}\right]\right\}\quad.\;.\;.\;.\;.\;.\quad(116)$$

In the case of a simple rectangular slot (Fig. 2)

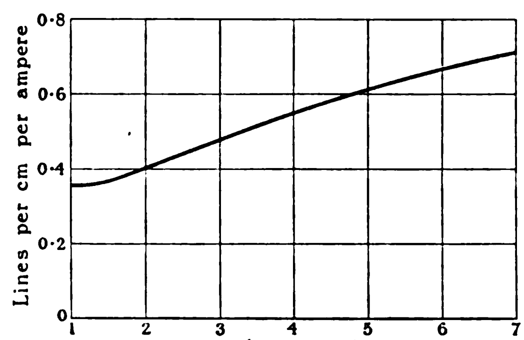

FIG. 33.

$a=b=c$, $\beta=0$, $\alpha=\delta=\frac{1}{2}s$, $\gamma=g$, $\lambda=0$, $p=\alpha/\gamma=s/(2g)$, and the expression for N becomes

$$N=\frac{1}{\pi}\left\{\log\left[\frac{1}{4}\left(\frac{s}{2g}+\frac{2g}{s}\right)\right]\right.$$
$$\left.+\frac{2g}{s}\operatorname{arc\,tan}\frac{2g}{s}+\frac{2g}{s}\operatorname{arc\,tan}\frac{s}{2g}\right\}\quad(117)$$

This is shown, plotted against $s/(2g)$ or $2g/s$, in Fig. 32. Multiplied by $4\pi/10$, the result is expressed in lines per ampere per cm length of core. This, which is in general the more convenient form, is given in Fig. 33.

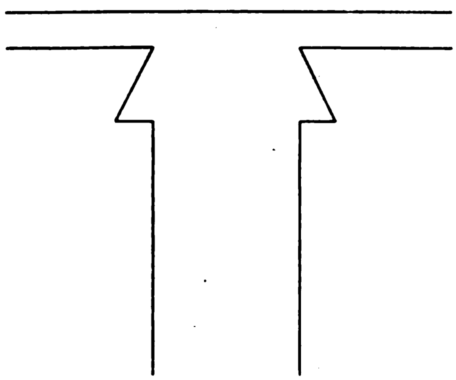

FIG. 34.

The simple rectangular slot is not generally used in machines of the class for which exact reactance calculations are important. Such machines, when designed to use formed coils, usually have open slots provided

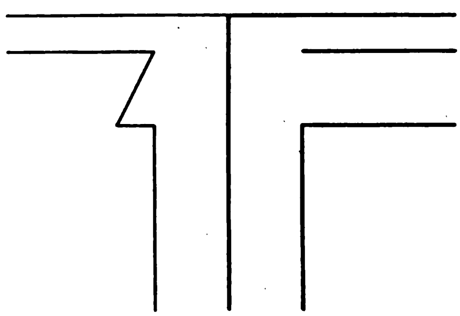

FIG. 35.

with recesses at their mouths in which are driven wooden retainers for holding the coils in place, as shown in Fig. 34. For these slots, the correction for mouth effect is somewhat smaller than is given by equation (117).

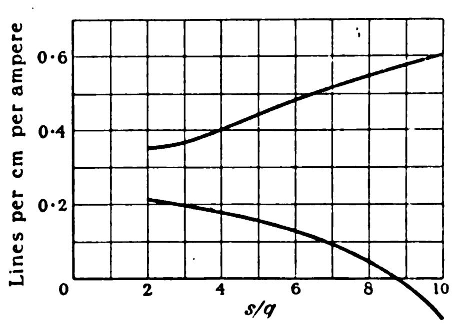

FIG. 36.

It is indeed possible to choose constants in equation (108) so that an equipotential of small inclination with the positive axis of ζ resembles more or less closely the boundary of such a slot as is depicted in Fig. 34, but the problem would be of difficulty out of proportion to the value of the result, since the solution has no absolute status but merely represents an individual judgment. The transformation, however, has its uses, for if the constants be chosen, in relation to the actual slot, to give the boundary shown in thick lines in Fig. 35, the flux determined therefrom may be regarded as an inferior limit, the simple rectangular slot furnishing the superior limit. The limits are shown in Fig. 36, for the case in which the recess extends to a distance equal to half the width of the slot.

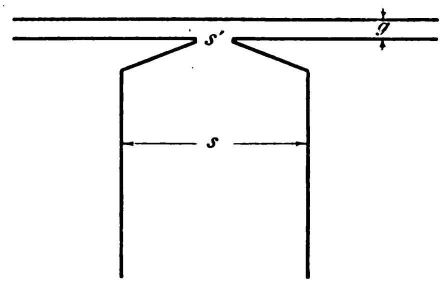

FIG. 37.

A common type of slot for which reactance calculations are of some importance is the partly closed slot, shaped generally as shown in Fig. 37. A reasonably close representation of this is obtained by making $a = b$ in the preceding formulæ and taking as boundary an equipotential line of small inclination with the real axis of ζ, resulting in a shape such as that shown in Fig. 38. It remains to choose constants to give a boundary approximating to that of the actual slot. The following course is suggested tentatively. Make $(1-\lambda)\gamma = g$, $2(1-\lambda)a = s$, $2\delta = s'$, and choose λ so

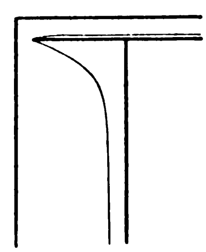

FIG. 38.

that the maximum slope of the boundary line agrees with that of the lip of the slot. The boundary thus determined is in most cases a little sharper at the tip of the lip than the actual slot, but, by way of compensation, it is caused to protrude a little further.

Consider the line of potential 1/2 in the field determined by

$$\phi + j\psi = \frac{1}{2(1-\lambda)}\left(1 + \frac{j}{\pi}\log\zeta\right) \quad . \quad (118)$$

For this equipotential

$$\begin{aligned}\zeta &= e^{2\pi(1-\lambda)\psi + \lambda\pi j} \\ &= q e^{\lambda\pi j} \quad . \quad . \quad . \quad . \quad . \quad . \quad (119)\end{aligned}$$

From equation (108)

$$\frac{dz}{dq} = \frac{\gamma}{\pi}\,\frac{q e^{\lambda\pi j} - c}{q\,[(q e^{\lambda\pi j} - a)\,(q e^{\lambda\pi j} + 1)]^{\frac{1}{2}}} \quad . \quad . \quad (120)$$

Writing $\qquad dz = e^{j\theta'} ds$

the slope of the boundary is given by

$$\theta' = \text{arc tan}\,\frac{q \sin \lambda\pi}{q \cos \lambda\pi - c} - \tfrac{1}{2}\,\text{arc tan}\,\frac{q \sin \lambda\pi}{q \cos \lambda\pi - a} - \tfrac{1}{2}\,\text{arc tan}\,\frac{q \sin \lambda\pi}{q \cos \lambda\pi + 1} \qquad (121)$$

This is a maximum when

$$\frac{(1 + c)\,(q^2 + c)}{q^2 + 1 + 2q \cos \lambda\pi} = \frac{(c - a)\,(ac - q^2)}{q^2 + a^2 - 2qa \cos \lambda\pi} \qquad (122)$$

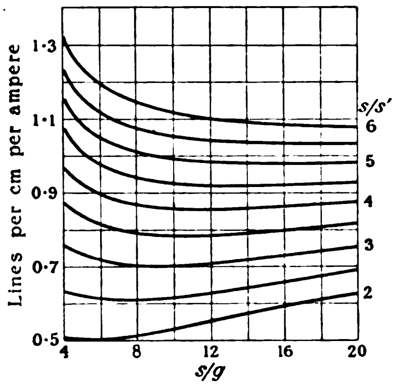

FIG. 39.

and the maximum value of θ' is, by assumption, connected with the angle θ of the lip by the relation

$$\theta + \theta' = \pi \quad . \quad . \quad . \quad . \quad (123)$$

For particular values of the constants, and of the angle θ, equations (121), (122) and (123) determine λ.

The calculation indicated is, however, more intricate than the solution warrants, in view of the lack of exact correspondence between assumed and actual boundaries.

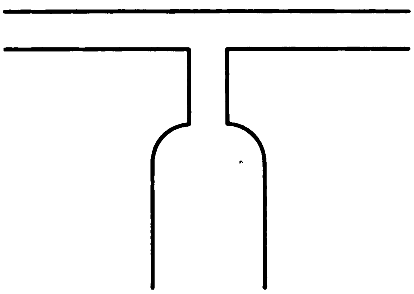

FIG. 40.

It cannot, however, lead to much, if any, greater deviation from the actual boundary to deduce λ, by a similar process of reasoning, from the problem next to be discussed. The connection between λ and the maximum slope of the equipotential line is readily shown in this case to be given by

$$\tan \frac{\lambda\pi}{2} = \frac{s - s'}{s + s'} \tan \theta \quad . \quad . \quad . \quad (124)$$

The additional flux is then determined from equation (116) with p deduced from equations (109), (110) and (111). Fig. 39 gives this flux for the case in which $\theta = 20°$.

In the preceding problem the tips of the slot are supposed brought to about as sharp an edge as mechanical considerations render practicable. In some cases, however, the parallel sides of the mouth are made of appreciable depth, as in Fig. 40, and the field between the sides attains sensibly the normal value corresponding to the distance between them. Consider first the

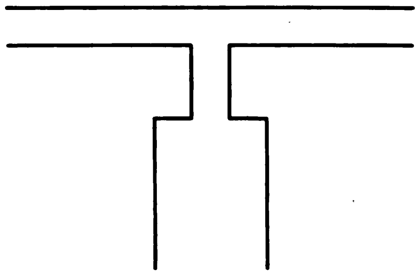

FIG. 41.

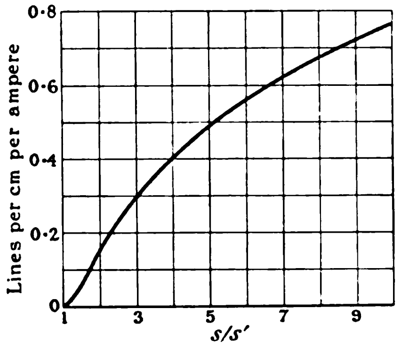

FIG. 42.

rectangular slot, shaped as in Fig. 41. There are here three regions in which the field may be described as normal, viz. the slot, the mouth and the gap, and two regions of transition, one between slot and mouth, the

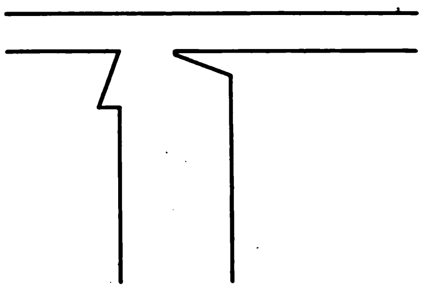

FIG. 43.

other between mouth and gap. For the first of these the additional flux is $\tfrac{1}{2}N$ given by equation (103) (see Figs. 26 and 42); for the second the additional flux is given by equation (117) and Figs. 32 and 33.

For a rounded slot, like that of Fig. 40, one of the equipotential lines might be taken as boundary; but the slots usually employed do not approximate to the shape of these lines, and the square-ended slot is the

better representation. In most cases, accordingly, it is sufficient to assume an equivalent square-ended slot.

Another form of slot, which has its use on occasion, is the unsymmetrical semi-closed slot, shaped as shown in Fig. 43. It is probably sufficient in this case to consider the slot to be bounded as shown in Fig. 44, thus assuming the extra flux due to the bluntness of the overhanging lip in Fig. 43, as compared with Fig. 44, to be sensibly compensated by the reduced flux due to the presence of the recess on the opposite side of the slot.

The transformation in this case may be written

$$z=\frac{g}{\pi}\int\left(\frac{\zeta+c}{\zeta-a}\right)^{\frac{1}{2}}\cdot\frac{\zeta-b}{\zeta+1}\cdot\frac{d\zeta}{\zeta}$$

$$=\frac{g}{\pi}\left\{\operatorname{arc\,cosh}\frac{2\zeta+c-a}{c+a}+\frac{s}{g}\operatorname{arc\,cos}\frac{(c-a)\zeta-2ca}{(c+a)\zeta}\right.$$

$$\left.-\operatorname{arc\,cosh}\frac{(2-c+a)(\zeta+1)-2(1+a)(1-c)}{(c+a)(\zeta+1)}\right\} \quad (125)$$

where -1, $-c$, a, b are in ascending order of magnitude.

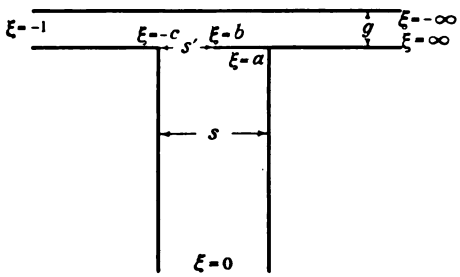

Fig. 44.

When ζ lies between -1 and ∞ the flux function ψ is given by

$$\frac{\zeta^2}{\zeta+1}=e^{2\pi\psi} \quad . \quad . \quad . \quad . \quad (126)$$

The constants in equation (125) are connected with the dimensions of the slot by the equations

$$\frac{s}{g}=b\left(\frac{c}{a}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (127)$$

$$(1+b)\left(\frac{1-c}{1+a}\right)^{\frac{1}{2}}=1 \quad . \quad . \quad . \quad (128)$$

$$\frac{s'}{g}=\frac{1}{\pi}\left\{\operatorname{arc\,cosh}\frac{2b+c-a}{c+a}+\frac{s}{g}\operatorname{arc\,cos}\frac{(c-a)b-2ca}{(c+a)b}\right.$$

$$\left.-\operatorname{arc\,cosh}\frac{(2-c+a)(1+b)-2(1+a)(1-c)}{(c+a)(1+b)}\right\} \quad (129)$$

When ζ is large, real and positive :—

$$x=\frac{g}{\pi}\left\{2\pi\psi_1+\log\frac{4}{c+a}+\frac{s}{g}\operatorname{arc\,cos}\frac{c-a}{c+a}\right.$$

$$\left.-\operatorname{arc\,cosh}\frac{2-c+a}{c+a}\right\}$$

When ζ is small, real and positive :—

$$y=\frac{g}{\pi}\left\{\operatorname{arc\,cos}\frac{c-a}{c+a}-\frac{s}{g}\left(-\pi\psi_0+\log\frac{4ca}{c+a}\right)\right.$$

$$\left.-\operatorname{arc\,cos}\frac{2ac+c-a}{c+a}\right\}$$

Whence

$$\psi_1-\psi_0=\frac{x-s'}{2g}+\frac{-y}{s}+\frac{s'}{2g}$$

$$+\frac{1}{2\pi}\left\{\log\frac{(c+a)^3}{64c^2a^2}-\left(\frac{s}{g}-\frac{2g}{s}\right)\operatorname{arc\,cos}\frac{c-a}{c+a}\right.$$

$$\left.+\operatorname{arc\,cosh}\frac{2-c+a}{c+a}-\frac{2g}{s}\operatorname{arc\,cos}\frac{2ac+c-a}{c+a}\right\} \quad (130)$$

The flux accordingly may be reckoned as filling the slot at the appropriate normal density, and the gap to the mouth of the slot at its appropriate normal density with the addition, per unit length of core, of N, given by

$$N=\frac{s'}{2g}+\frac{1}{2\pi}\left\{\log\frac{(c+a)^3}{64c^2a^2}-\left(\frac{s}{g}-\frac{2g}{s}\right)\operatorname{arc\,cos}\frac{c-a}{c+a}\right.$$

$$+\operatorname{arc\,cosh}\frac{2-c+a}{c+a}$$

$$\left.-\frac{2g}{s}\operatorname{arc\,cos}\frac{2ac+c-a}{c+a}\right\} \quad . \quad (131)$$

In many cases $s/s'=2$, and although this does not simplify the equations from which the constants are derived, it reduces the results to functions of a single variable, such as s/g, and enables them to be expressed in a single curve. Fig. 45 gives the curve for this case.

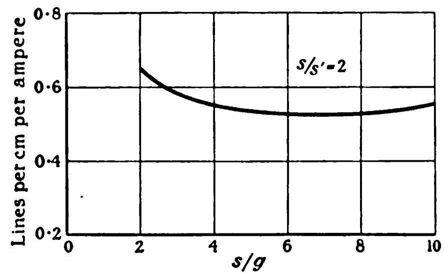

Fig. 45

In the foregoing the slots have been assumed to be opposed to plane equipotential surfaces, but in most cases in which the reactance of the embedded conductors is of importance there are slots in both opposing surfaces. The reactance then varies, being a minimum when slot is opposed by slot, and a maximum when slot is opposed by tooth. Since the variation takes place principally in the field outside the slot, it is sufficient for practical purposes to consider the case in which the opposing slots are rectangular and of widths equal to those of the mouths of the actual slots. The curve of variation, as the slots are displaced relatively, might be deduced by means of the transformation given in Section 4, but, for the purpose in view, it is probably sufficient to establish a formula giving the extent of the variation.

If s' is the width of the mouth of the slot containing the conductors whose reactance is required, and s_1 that of the opposing slot, the transformation

$$z=\frac{g}{\pi}\int\frac{[(\zeta-a)(\zeta+c)]^{\frac{1}{2}}d\zeta}{\zeta(\zeta+b)}$$

$$=\frac{g}{\pi}\left\{\operatorname{arc\,cosh}\frac{2\zeta+c-a}{c+a}+\frac{s'}{2g}\operatorname{arc\,cos}\frac{(c-a)\zeta-2ac}{(c+a)\zeta}\right.$$

$$\left.+\frac{s_1}{2g}\operatorname{arc\,cos}\frac{2(c-b)(a+b)+(a+2b-c)(\zeta+b)}{(a+c)(\zeta+b)}\right\} \quad (132)$$

in which $-c$, $-b$, 0, a, are in ascending order of magnitude, and in which

$$\frac{s'}{2g}=\frac{\sqrt{(ac)}}{b} \quad . \quad . \quad . \quad . \quad . \quad (133)$$

$$\frac{s_1}{2g}=\frac{\sqrt{[(a+b)(c-b)]}}{b} \quad . \quad . \quad . \quad (134)$$

converts the half-plane of ζ into the plane of z, bounded

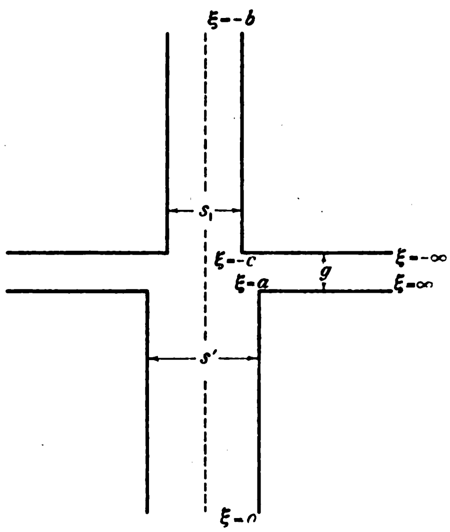

FIG. 46.

as in Fig. 46. The flux function ψ is given on the real axis of ζ by

$$\zeta=e^{2\pi\psi} \quad . \quad . \quad . \quad . \quad . \quad . \quad (135)$$

When ζ is large, real and positive :—

$$x=\frac{g}{\pi}\left\{2\pi\psi_1+\log\frac{4}{c+a}+\frac{s'}{2g}\operatorname{arc\,cos}\frac{c-a}{c+a}\right.$$

$$\left.+\frac{s_1}{2g}\operatorname{arc\,cos}\frac{a+2b-c}{c+a}\right\}$$

When ζ is small, real and positive :—

$$y=\frac{g}{\pi}\left\{\operatorname{arc\,cos}\frac{c-a}{c+a}-\frac{s'}{2g}\left(-2\pi\psi_0+\log\frac{4ac}{c+a}\right)\right.$$

$$\left.+\frac{s_1}{2g}\operatorname{arc\,cosh}\frac{2ac+b(c-a)}{b(c+a)}\right\}$$

Whence

$$\psi_1-\psi_0=\frac{x-\frac{1}{2}s'}{2g}+\frac{-y}{s'}$$

$$+\frac{1}{2\pi}\left\{\log\frac{(c+a)^2}{16ca}+\frac{s'}{2g}\left(\pi-\operatorname{arc\,cos}\frac{c-a}{c+a}\right)\right.$$

$$+\frac{2g}{s'}\operatorname{arc\,cos}\frac{c-a}{c+a}-\frac{s_1}{2g}\operatorname{arc\,cos}\frac{a+2b-c}{c+a}$$

$$\left.+\frac{s_1}{s'}\operatorname{arc\,cosh}\frac{2ac+b(c-a)}{b(c+a)}\right\} \quad . \quad (136)$$

The additional flux in this case is accordingly

$$N=\frac{1}{2\pi}\left\{\log\frac{(c+a)^2}{16ca}\right.$$

$$+\frac{s'}{2g}\left(\pi-\operatorname{arc\,cos}\frac{c-a}{c+a}\right)+\frac{2g}{s'}\operatorname{arc\,cos}\frac{c-a}{c+a}$$

$$-\frac{s_1}{s'}\left[\frac{s'}{2g}\operatorname{arc\,cos}\frac{a+2b-c}{c+a}\right.$$

$$\left.\left.-\operatorname{arc\,cosh}\frac{2ac+b(c-a)}{b(c+a)}\right]\right\} \quad . \quad . \quad (137)$$

Writing $\lambda=(c/a)^{\frac{1}{2}}$, equations (133) and (134) give

$$\frac{s'}{2g}\lambda=\frac{c}{b};\quad \frac{s'}{2g}\lambda^{-1}=\frac{a}{b}$$

$$\left(\frac{s_1}{2g}\right)^2=\left(\frac{s'}{2g}\lambda^{-1}+1\right)\left(\frac{s'}{2g}\lambda-1\right)$$

$$=\left(\frac{s'}{2g}\right)^2-1+\frac{s'}{2g}(\lambda-\lambda^{-1}) \quad . \quad (138)$$

Equation (138) gives λ, and the additional flux may be written

$$N=\frac{1}{\pi}\left\{\log\left[\tfrac{1}{2}(\lambda+\lambda^{-1})\right]\right.$$

$$\left.+\frac{s'}{2g}\operatorname{arc\,tan}(\lambda)+\frac{2g}{s'}\operatorname{arc\,tan}(\lambda^{-1})\right\}$$

$$-\frac{1}{2\pi}\frac{s_1}{s'}\left\{\frac{s'}{2g}\operatorname{arc\,cos}\frac{4g^2+s'^2-s_1^2}{2gs'(\lambda+\lambda^{-1})}\right.$$

$$\left.-\operatorname{arc\,cosh}\frac{4g^2+s'^2+s_1^2}{2gs'(\lambda+\lambda^{-1})}\right\} \quad (139)$$

Equation (139) gives the minimum additional flux, and the maximum is given by equation (117). The variation sought is therefore

$$N'=\frac{1}{\pi}\left\{\log\left[\left(\frac{s'}{2g}+\frac{2g}{s'}\right)\Big/(\lambda+\lambda^{-1})\right]\right.$$

$$+\frac{s'}{2g}\left[\operatorname{arc\,tan}\frac{2g}{s'}-\operatorname{arc\,tan}\lambda\right]$$

$$\left.+\frac{2g}{s'}\left[\operatorname{arc\,tan}\frac{s'}{2g}-\operatorname{arc\,tan}\lambda^{-1}\right]\right\}$$

$$+\frac{1}{2\pi}\cdot\frac{s_1}{s'}\left\{\frac{s'}{2g}\operatorname{arc\,cos}\frac{4g^2+s'^2-s_1^2}{2gs'(\lambda+\lambda^{-1})}\right.$$

$$\left.-\operatorname{arc\,cosh}\frac{4g^2+s'+s_1^2}{2gs(\lambda+\lambda^{-1})}\right\} \quad (140)$$

APPENDIX 1.

On the Transformation of Schwarz and Christoffel (Section 3, Page 1116).

The powerful and beautiful method of transformation associated with the joint names of Schwarz * and Christoffel † is used in most of the problems discussed herein, and, although well known to mathematicians, the reasoning on which it is based is not readily available in explicit form to English readers. It is discussed fully in Sir J. J. Thomson's "Recent Researches in Electricity and Magnetism," ‡ which has, however, long been out of print. It is treated slightly in Dr. J. H. Jean's "Electricity and Magnetism," § where, however, it is introduced as a transformation in which one equipotential can be any linear polygon. The apparent restriction of the boundary to a single equipotential is an unnecessary one, which would exclude all the problems discussed in the present paper. It is, in effect, removed in a later Section, dealing with successive transformations; but although this procedure offers no difficulty to the expert, it is perhaps confusing to those less exclusively occupied with mathematics, who may, nevertheless, be quite competent to understand the method. It may, therefore, not be considered inappropriate to attempt the elucidation of the matter here.

It is expedient at the outset to state the general problem in mathematical language, in order to show the aim of the investigation. Briefly, we seek a certain function of the co-ordinates, designated a potential function, which satisfies Laplace's equation within a certain region, and which has certain properties on the boundaries of the region. A knowledge of this function determines the whole solution. In two dimensions Laplace's equation takes the form:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} = 0$$

Now the real or the imaginary part of any function of the complex variable, $x + jy$, satisfies this equation, and it is only necessary to find the form of the function appropriate to the boundary conditions. In most of the problems herein discussed the potential distribution at the boundary is known, having a constant value over one portion and another constant value over the remainder. Sometimes, as in the case of Fig. 4, the potential assumes certain constant values on portions of the boundary, and its conjugate function, which we designate the "flux function," assumes constant values on other portions.

If (x, y) are the co-ordinates of a point, and any function of the complex variable, $z = x + jy$, be formed, it is itself a complex quantity, and may be written in the form, $\zeta = F(z) = \xi + j\eta$. If (ξ, η) be taken as the co-ordinates of a point in a new plane, a problem in the plane of (x, y), involving certain boundaries, yields a problem in the plane of (ξ, η), with corresponding transformed boundaries. From the relation:

$$d\zeta = F'(z)dz$$

it is apparent that $d\zeta$, in the neighbourhood of any point, is dz multiplied by the modulus of $F'(z)$ and turned through a certain angle—the argument of $F'(z)$. Infinitesimal areas about a point accordingly transform into similar areas. The potential and flux functions, ϕ and ψ, are, as already remarked, conjugate. Thus $\phi + j\psi$ is a function of z and, therefore, of ζ. ϕ and ψ accordingly remain possible potential and flux functions on transformation. By means of such transformation

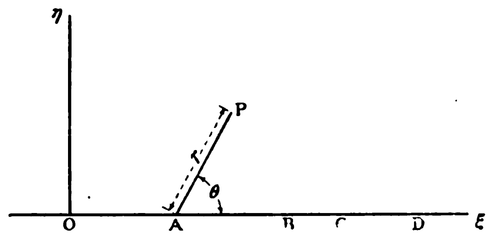

Fig. 47.—Plane of ζ.

an intricate problem can often be made to depend on a simpler one.

The transformation of Schwarz and Christoffel is a geometrical one, transforming the whole region on the positive side of the real axis in one plane (called herein the plane of ζ, where $\zeta = \xi + j\eta$, see Fig. 47), into a region bounded by any required rectilinear polygon in the transformed plane (called herein the plane of z, where $z = x + jy$, see Fig. 48). Here the word "polygon" should be interpreted as any continuous recti-

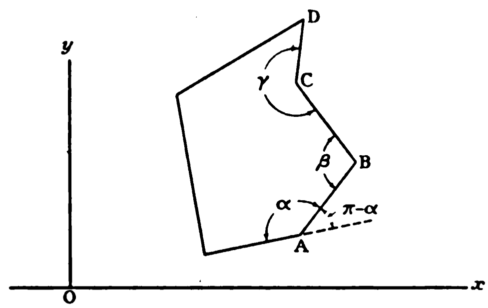

Fig. 48.—Plane of z.

linear figure which does not cross itself, closed either in finite regions or by means of the line at infinity, and the region bounded by it as the region on one side of the boundary.

Consider the transformation

$$\frac{dz}{d\zeta} = A(\zeta - a)^{(\alpha/\pi)-1}(\zeta - b)^{(\beta/\pi)-1}(\zeta - c)^{(\gamma/\pi)-1} \quad (141)$$

in which A is a constant, real or complex, $a, b, c \ldots$ are real constants, representing the distances OA, OB, OC . . . in Fig. 47, and $\alpha, \beta, \gamma, \ldots$ are real constants, representing the internal angles of the polygon in Fig. 48. It will be noted that $dz/d\zeta$ becomes either zero or infinity at a singular point, implying that an

* Crelle, 1869, tome 70.
† *Annali di Matematica* (2), 1867, tome 1.
‡ Oxford, 1893, ch. 3.
§ Cambridge University Press, 1923, ch. 8, par. 322 *et seq.*

infinitesimal $d\zeta$ at such a point gives rise to an infinitesimal dz of higher or lower order.

Now at any point P (see Fig. 47)

$$\begin{aligned}\zeta - a &= \xi - a + j\eta \\ &= r(\cos\theta + j\sin\theta) \\ &= re^{j\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (142)\end{aligned}$$

When ζ is on the real axis, the argument of $\zeta - a$ is zero, or a multiple of π, but as we are only concerned with changes in the argument we may take it as zero when $\zeta - a$ is positive, and as π when $\zeta - a$ is negative, the passage through A from $\zeta > a$ to $\zeta < a$ being viewed as the limit of a passage in a small semi-circle, drawn about A in the region under consideration, in which the argument θ increases from 0 to π.

Now, the argument of a product being the sum of the arguments of its factors, it follows that along the real axis of ζ, the argument of $dz/d\zeta$ in equation (141) (and therefore that of dz, since $d\zeta$ is real), only changes when ζ passes through one of the points A, B, C . . . Accordingly dz maintains a constant direction between consecutive singular points in Fig. 47, and the transformed figure corresponding to the real axis of ζ is a rectilinear polygon. In passing through a singular point (e.g. $\zeta = a$) the argument of $\zeta - a$ is diminished by π, and that of $(\zeta - a)^{(\alpha/\pi)-1}$ is diminished by $[(\alpha/\pi) - 1]\pi$, i.e. increased by $\pi - \alpha$. The change in direction of the boundary at A in Fig. 48 is therefore $\pi - \alpha$, and α is the value of the internal angle at A in the transformed figure; and so generally.

The transformation required is accordingly

$$z = A\int(\zeta - a)^{(\alpha/\pi)-1}(\zeta - b)^{(\beta/\pi)-1}(\zeta - c)^{(\gamma/\pi)-1} \ldots d\zeta \quad (143)$$

in which α, β, γ, . . . are the internal angles of the polygon; a, b, c, . . . are real quantities which have to be determined so as to give correct proportions to the figure, but of which three may be given arbitrary values *; and A is a constant determining the size and orientation of the figure.

The boundary having thus been determined, the appropriate field depends on the particular problem, for the same boundary transformation may be used in different problems.† In most of the problems discussed, the potential function is required to be such as gives a certain distribution of potential on the bounding polygon; in order to determine this, a potential function is sought in terms of ζ, which gives the required distribution on corresponding portions of the boundary (i.e. the real axis), in the plane of ζ; and this function, transformed into z co-ordinates, gives the solution of the problem. In most of the problems considered, the field in the plane of ζ may be taken as that due to a current of electricity passing through one of the singular points at right angles to the plane, thus causing a constant difference of magnetic potential between the portions of boundary on the two sides of the singular point. If ϕ is the potential function and ψ the flux function, the field is determined by an equation of the form

$$\phi + j\psi = Cj\log(\zeta - a) \quad . \quad . \quad . \quad (144)$$

* In the problems discussed, however, two only of the points have been chosen arbitrarily, the origin being one, but the line at infinity has been localized as the third condition.

† See Section 10, page 1128.

in which C is real. If r is the modulus and θ the argument of $\zeta - a$, the equation may be written

$$\phi + j\psi = C(j\log r - \theta) \quad . \quad . \quad . \quad (145)$$

The radial lines, θ = constant (in particular $\theta = 0$ and $\theta = \pi$), are equipotential, and the circles, r = constant, are lines of flux. It may be mentioned that, except in one case (see Fig. 20), the transformed source is at infinity. The field in the plane of ζ may take other forms, that determined by equation (39) for instance, in which two equipotential sections of the boundary are isolated and separated by flux lines.

As an example of the use of the method, consider the first problem discussed in Section 6 (see Fig. 15). Starting from $\zeta = -\infty$, z follows the y axis until $\zeta = -1$ (a figure chosen arbitrarily), where the polygonal boundary has an internal angle $\frac{1}{2}\pi$. It then follows the x axis to infinity ($\zeta = 0$), here doubles back on itself (internal angle zero), until the point A is reached ($\zeta = a$), where it again doubles back (internal angle 2π), and proceeds to infinity. Equation (143) accordingly gives

$$z = A\int(\zeta + 1)^{\frac{1}{2}-1}(\zeta - 0)^{0-1}(\zeta - a)^{2-1}d\zeta \quad (146)$$

which is equation (45).

The field on this case is required to make the line between A and infinity at one potential, and the rest of the boundary at another. Equation (144), with $a = 0$, is of the form of equation (46), in which, however, an immaterial constant has been added to make one section of the boundary of zero potential.

One other matter may be mentioned, having reference to the practice, of which frequent use is made, of taking one line of the boundary to infinity and returning by a parallel line. The angle between these sides is zero and the corresponding factor in equation (143) is $(\zeta - a)^{-1}$. In order to find the change in z as ζ passes through A, proceed to a point indefinitely near to A; then, passing to the other side by a semi-circle drawn in the region under consideration, as already explained, the increment of z is

$$\begin{aligned}\delta z &= A(a - b)^{(\beta/\pi)-1}(a - c)^{(\gamma/\pi)-1} \ldots \int(re^{j\theta})^{-1}d(re^{j\theta}) \\ &= A(a - b)^{(\beta/\pi)-1}(a - c)^{(\gamma/\pi)-1} \ldots \int_{\pi}^{0} j\,d\theta \\ &= -A(a - b)^{(\beta/\pi)-1}(a - c)^{(\gamma/\pi)-1} \ldots j\pi \quad . \quad . \quad (147)\end{aligned}$$

This then is the distance between the parallel sides. Much use is made of equation (147) in the course of the paper, e.g. in equations (12), (17), (109), (110), (127), (128), (133) and (134).

APPENDIX 2.

ATTRACTION BETWEEN POLAR SURFACES (SEE SECTION 1, PAGE 1116.)

The strictures made concerning the practicability of using the method of conjugate functions where there is no natural limit to the field, apply to problems involving the integral flux, such as that of the inductance of the

coil producing the field. Problems which merely involve change in flux may be quite appropriate for treatment. Thus, if the difference of potential between the members in Fig. 1 be maintained constant, this difference, multiplied by the rate of increase of flux with movement of a member, and divided by 8π, is the mechanical force tending to produce the movement. If, for instance, Fig. 1 represents the edge of the poles of a contactor, or plunger electromagnet, the force of attraction between the poles is readily obtained. The appropriate transformation and field function are given in equations (95) and (96), whilst equation (98) gives ψ under the pole. When ψ is large and negative :—

$$x_1 = \frac{\gamma}{\pi} e^{-\pi\psi_1}$$

or

$$\psi_1 = -\frac{1}{\pi} \log \frac{\pi x_1}{\gamma}$$

whence $$\psi - \psi_1 = -\frac{x}{\gamma} + \frac{1}{\pi} \log \frac{\pi x_1}{\gamma} + \text{const.}$$

This is the total flux between the points x and x_1 with unity difference of potential between the polar

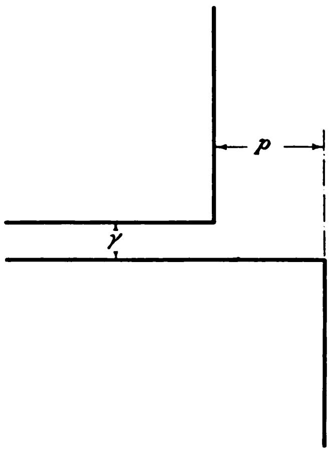

FIG. 49.

surfaces. The attraction between the members, if ϕ_0 is their difference of potential, is accordingly

$$-\frac{\phi_0}{8\pi} \cdot \frac{d}{d\gamma}[\phi_0(\psi - \psi_1)] = \frac{\phi_0^2}{8\pi}\left(-\frac{x}{\gamma^2} + \frac{1}{\gamma\pi}\right)$$

$$= \frac{\phi_0^2}{8\pi\gamma^2}\left(-x + \frac{\gamma}{\pi}\right) \quad (148)$$

Here $-x$ is the distance under the pole, measured from the edge, and $\phi_0^2/(8\pi\gamma^2)$ is the force per unit area. The attraction of the plunger is accordingly the same as if the pole were increased by a rim of width γ/π all round, and the normal flux density ϕ_0/γ maintained throughout the area so increased.

A similar transformation, devised to deal with the case of overhanging poles (Fig. 49), was used by the author in a note * on "Magnetic Centering of Dynamo-electric Machinery," in a somewhat similar manner. The attraction between such poles is readily found to be equivalent to adding to the smaller a rim of width

$$\frac{\gamma}{\pi} + \frac{p}{\pi} \operatorname{arc\,cot} \frac{p}{\gamma} \quad . \quad . \quad . \quad . \quad (149)$$

* *Minutes of the Proceedings of the Institution of Civil Engineers*, 1911-12, vol. 187, p. 311.

APPENDIX 3.

CALCULATION OF GAP COEFFICIENT (SEE SECTION 3, PAGE 1118).

As an example of a calculation approximately applicable to given conditions, take the case in which $t/s = 1$ and $2g/s = 1$. Equation (8) gives $\sigma = 0 \cdot 2794$; and from equation (25)

$$\frac{F'}{F} = 1 \cdot 7206 \quad . \quad . \quad . \quad . \quad (150)$$

whence the modulus of F,

$$k \operatorname{sn} \alpha = \sin 15° \; 16 \cdot 4' = 0 \cdot 2634 \quad . \quad . \quad (151)$$

Equation (16) gives $\operatorname{sn} \alpha = 0 \cdot 7071$, and accordingly $k = 0 \cdot 3726$ approx. Sn α is, however, not quite the most convenient starting point for the calculation, and it appears to give a better approximation to the actual case to modify equation (16), making

$$\sin \frac{\pi\alpha}{2K} = \left[1 + \left(\frac{s}{2g}\right)^2\right]^{-\frac{1}{2}}$$

or

$$\tan \frac{\pi\alpha}{2K} = \frac{2g}{s} \quad . \quad . \quad . \quad . \quad . \quad (152)$$

A preliminary calculation for $\operatorname{sn} \alpha$ with $k = 0 \cdot 3726$ gives $\operatorname{sn} \alpha = 0 \cdot 72$, whence $k = \sin 21° \; 30' = 0 \cdot 3665$.

$$K = 1 \cdot 6280 \; ; \; K' = 2 \cdot 4404 \; ; \; q = e^{-\pi(K'/K)} = 0 \cdot 00901$$

whence $$\frac{\pi}{2} \frac{\alpha}{K} = \frac{\pi}{4}; \quad \alpha = \frac{K}{2} = 0 \cdot 8140$$

$$\Theta(\alpha) = 1 - 2q \cos\left(\pi\frac{\alpha}{K}\right) + 2q^4 \cos\left(2\pi\frac{\alpha}{K}\right) \ldots$$
$$= 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (153)^*$$

$$H(\alpha) = 2\left[q^{\frac{1}{4}} \sin\left(\frac{\pi\alpha}{K}\right) - q^{\frac{9}{4}} \sin\left(\frac{3\pi\alpha}{K}\right) + \ldots\right]$$
$$= 0 \cdot 4357 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (154)^*$$

$$\Theta'(\alpha) = \frac{2\pi}{K}\left[q \sin\left(\frac{\pi\alpha}{K}\right) - 2q^4 \sin\left(2\frac{\pi\alpha}{K}\right) + \ldots\right]$$
$$= 0 \cdot 03477 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (155)^*$$

$$\operatorname{sn} \alpha = \frac{H(\alpha)}{k^{\frac{1}{2}}\Theta(\alpha)}$$
$$= 0 \cdot 7198 \quad . \quad . \quad . \quad (156)\dagger$$

$$\operatorname{cn} \alpha = 0 \cdot 6942 \quad . \quad . \quad . \quad . \quad (157)$$

$$\operatorname{dn} \alpha = 0 \cdot 9646 \quad . \quad . \quad . \quad . \quad (158)$$

$$\frac{\operatorname{sn} \alpha \operatorname{dn} \alpha}{\operatorname{cn} \alpha} = 1 \cdot 00 \quad . \quad . \quad . \quad . \quad . \quad (159)$$

$$Z(\alpha) = \frac{\Theta'(\alpha)}{\Theta(\alpha)}$$
$$= 0 \cdot 03477 \quad . \quad . \quad . \quad (160)\ddagger$$

* *Vide* Cayley's "Elliptic Functions," 2nd edn., par. 388.
† *Ibid.*, par. 387. ‡ *Ibid.*, par. 210.

Hence, from equation (19) :—

$$\frac{2g}{s} = 1\cdot0004 \quad . \quad . \quad . \quad . \quad . \quad (161)$$

and from equation (20) :—

$$\frac{t}{s} = 0\cdot9997 \quad . \quad . \quad . \quad . \quad . \quad . \quad (162)$$

Again,

$$k \operatorname{sn} a = 0\cdot2638 \quad . \quad . \quad . \quad . \quad . \quad (163)$$

$$F = 1\cdot5993 \quad . \quad . \quad . \quad . \quad . \quad (164)$$

$$F' = 2\cdot7503 \quad . \quad . \quad . \quad . \quad . \quad (165)$$

Hence, from equation (22) :—

$$\frac{G}{g} = 1\cdot1622 \quad . \quad . \quad . \quad . \quad . \quad . \quad (166)$$

The formula of (10), for the dimensions given by (161) and (162), yields

$$\frac{G}{g} = 1\cdot161$$

APPENDIX 4.

Calculation of Fringe Flux at Pole-Tip (see Section 6, Page 1122).

The process of computing the curves of Fig. 17 was as follows :—

(1) A number of suitable values of the constant a were determined by drawing a curve between x/γ and a, where x is deduced from equation (45), with $\zeta = a$ and $\lambda = 0$.

(2) With each of these values of a and for a few values of λ, q was determined from equation (52).

(3) The corresponding radius of curvature was determined from equations (49) and (51).*

(4) The radius of curvature was plotted, against λ as abscissa, for each of the selected values of a.

(5) The value of x/γ corresponding to the extreme tip was determined, from equations (45), (47) and (52), for each value of a and of λ.

(6) This value of x/γ was plotted, against λ as abscissa, for each of the selected values of a.

(7) The fringing effect d/γ as given by equation (55) was determined for each value of a and of λ.

(8) The fringing was expressed as an equivalent addition to the pole-face, by subtracting the result given above by (7) from that given by (5).

(9) The fringing so expressed was plotted, against λ as abscissa, for each of the selected values of a.

(10) By cross-plotting, for each required value of the radius of curvature, and for each value of a, the corresponding values of x/γ and of the fringing coefficient $(x - d)/\gamma$ were determined.

(11) The fringing coefficient was plotted against x/γ as abscissa, for each required value of radius of curvature.

* In this connection it may be noted that $q^2 + 2q\cos\lambda\pi + 1 = (1 + a)^2$.

THE CIRCLE DIAGRAMS OF THE THREE-PHASE SHUNT COMMUTATOR MOTOR.*

By A. H. M. Arnold, Ph.D., Student.

(*Paper first received 5th November, 1925, and in final form 23rd February, 1926.*)

Summary.

A simplified mathematical theory of the circle diagrams of the three-phase shunt commutator motor is developed from the theory of the standard polyphase induction motor. Sources of error in the theory are outlined, and the theoretical circles are then compared with test-results. Formulæ are developed for the slip, torque and mechanical power. The improvement in performance of the motor, which may be obtained by an unsymmetrical setting of the brushes, is described fully, and an approximate formula for the circle diagrams under these conditions is given. The capabilities of the motor as a generator are briefly discussed.

In the Appendix, phenomena occurring in the operation of the motor at synchronous speed are noted, with particular reference to the effect of errors in the brush settings.

Table of Contents.

List of Symbols Used.

Φ = mutual flux.

E_1 = E.M.F. induced in primary (rotor) phase winding.

E_2 = E.M.F. induced in secondary (stator) phase winding.

E_L = E.M.F. induced in lap winding between the half brushes of one phase, when these half brushes are separated 180 electrical degrees. This is termed the maximum lap winding E.M.F. or maximum "injected" E.M.F.

aE_L = lap winding E.M.F. or "injected" E.M.F. for an angle of brush separation of β electrical degrees.

$$a = \frac{k_{wl\beta}}{k_{wl}} \cdot \frac{\beta}{180}$$

(A curve, obtained experimentally, showing the relation between β and a is given in Fig. 3.)

n_1 = number of turns per phase in primary (rotor) winding.

n_2 = number of turns per phase in secondary (stator) winding.

n_l = number of turns per phase in lap (secondary) winding for a brush separation of 180 electrical degrees.

k_{w1} = breadth factor of primary winding.

k_{w2} = breadth factor of secondary (stator) winding.

k_{wl} = breadth factor of lap winding for a brush separation of 180 electrical degrees.

$k_{wl\beta}$ = breadth factor of lap winding for a brush separation of β electrical degrees.

n_{e1} = effective primary turns per phase $= n_1 \times k_{w1}$.

n_{e2} = effective secondary (stator) turns per phase $= n_2 \times k_{w2}$.

$$n = \frac{n_l \times k_{wl}}{n_2 \times k_{w2}}$$

$p = an$.

s = slip (defined on page 1142).

I_2 = secondary phase current (common to lap and stator windings).

I = primary (rotor) phase current.

I_m = magnetizing and hysteresis phase current.

$I_1 = I - I_m$ (vectorial subtraction).

R_1 = primary phase winding resistance.

R_2 = secondary phase resistance. This is the sum of the stator resistance, the brush contact resistance and the resistance of that part of the lap winding between the half brushes of the phase.

X_1 = primary phase winding leakage reactance at supply frequency.

X_2 = stator phase winding leakage reactance at supply frequency.

V = supply phase pressure.

P = mechanical power of the motor.

T = mechanical torque of the motor. (If pressures are in volts and currents in amperes, the torque will be in synchronous watts.)

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

T_m = maximum torque of the motor for a given brush position.

s_m = slip for maximum torque.

$$\left.\begin{aligned} \theta &= \text{vector angle between } E_2 \text{ and } I_2 \\ 180^\circ - \psi &= \text{vector angle between } V \text{ and } I_2 \\ \phi &= \text{vector angle between } V \text{ and } I_1 \\ \gamma &= \text{vector angle between } V \text{ and } I \end{aligned}\right\}\text{(see Fig.4).}$$

(i.e. phase angle of supply voltage and supply current.)

ρ = vector angle between E_L and I_1.

η = angle between centre-line of brush gear and centre line of secondary winding. (For symmetrical brush positions, $\eta = 0$.)

$\left.\begin{matrix} x \\ y \end{matrix}\right\}$ = co-ordinates of extremity of I_2 vector measured from O_1 as origin (see Fig. 6).

$\left.\begin{matrix} x_1 \\ y_1 \end{matrix}\right\}$ = co-ordinates of extremity of I_1 vector measured from O_1 as origin (see Fig. 6).

$\left.\begin{matrix} a \\ b \end{matrix}\right\}$ = co-ordinates of centre of secondary circle, measured from O_1 as origin.

$\left.\begin{matrix} a_1 \\ b_1 \end{matrix}\right\}$ = co-ordinates of centre of primary circle, measured from O_1 as origin.

r = radius of secondary circle.

r_1 = radius of primary circle.

Introduction.

In writing this paper much assistance has been derived from two papers * which explain the general theory of the motor fully and clearly.

It will be assumed in order to avoid, as far as possible, needless repetition, that the reader has access to the second of these two papers, but no knowledge of the German paper, as such parts of it as are necessary will be reproduced in the present paper.

The symbols used by Dr. Teago in his paper have been retained as far as possible, but certain new symbols are required for the mathematical solution of the diagrams, and in some cases the meanings of the symbols have been slightly altered. Full definitions are given of all the symbols used, and it is hoped that this will prevent confusion.

Dr. Teago's paper describes the general principles on which the motor operates. The present paper shows how the performance of the motor may be predetermined with reasonable accuracy and simplicity from the design data.

The Development of the Vector Diagram of the Three-Phase Shunt Commutator Motor from the Vector Diagram of the Induction Motor.

The standard vector diagram for one phase of the three-phase induction motor is shown in Fig. 2. This diagram is really two diagrams drawn about the same origin, the diagram of primary vectors and the diagram of secondary vectors. If it is desired to transfer a secondary vector to the primary diagram, it must be reduced to its equivalent primary value, by means of the transformation ratio of the motor. This is the ratio of effective primary turns to effective secondary turns per phase winding. Owing to the space distribution of the conductors of each phase winding, the M.M.F. produced by all the conductors of one phase winding is less than the algebraic sum of the individual M.M.F.'s of each conductor. Thus the effective turns are less than the actual turns. This is taken account of by means of a breadth factor, as follows:—

Effective primary turns (n_{e1}) = actual primary turns (n_1) × primary breadth factor (k_{w1}).

Effective secondary turns (n_{e2}) = actual secondary turns (n_2) × secondary breadth factor (k_{w2}).

$$\text{Transformation ratio} = \frac{n_{e1}}{n_{e2}} = \frac{n_1}{n_2} \times \frac{k_{w1}}{k_{w2}}.$$

Equivalent primary value of secondary current = (n_{e2}/n_{e1}) secondary current.

Equivalent primary value of secondary voltage = (n_{e1}/n_{e2}) secondary voltage.

Equivalent primary value of secondary resistance (or reactance) = $\left(\frac{n_{e1}}{n_{e2}}\right)^2$ secondary resistance (or reactance).

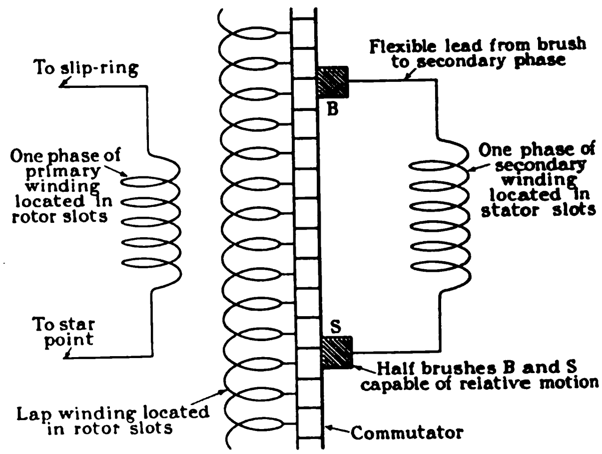

Fig. 1.—Diagram of windings.

If $n_{e1} = n_{e2}$ then the secondary vector diagram becomes identical in size and shape with the reduced secondary diagram, although its orientation about the origin will vary relatively to the primary diagram according to the position of the rotor. In practice it is always assumed that $n_{e1} = n_{e2}$, and the secondary diagram is drawn in such a position that it coincides with the reduced secondary diagram. If in the actual motor considered the ratio n_{e1}/n_{e2} is not unity, then the true values of vectors in the secondary circuit may be obtained from the diagram as follows.

True value of secondary current = (n_{e1}/n_{e2}) × value shown on diagram.

True value of secondary voltages = (n_{e2}/n_{e1}) × value shown on diagram.

True value of secondary resistances = $\left(\frac{n_{e2}}{n_{e1}}\right)^2$ × value shown on diagram.

Fig. 1 shows diagrammatically the windings for one phase of the three-phase shunt commutator motor. In this motor the transformation ratio is very much more

* H. K. Schrage: "Ein Neuer Drehstrom-Kommutatormotor Mit Nebenschluss-Regulierung Durch Bürstenverschiebung," *Elektrotechnische Zeitschrift*, 1914, vol. 35, p. 89; and F. J. Teago: "Test-Results Obtained from a Three-Phase Shunt Commutator Motor" *Journal I.E.E.*, 1922, vol. 60, p. 328.

complicated owing to the existence of two secondary windings, the stator winding and the lap winding. This gives rise to three different transformation ratios, two of which vary as the brush position is varied. The E.M.F. induced in the stator winding has a transformation ratio of effective primary turns per phase to effective stator winding turns per phase. The E.M.F. induced in the lap winding has a transformation ratio of effective primary turns to effective lap turns per phase, and the effective lap turns per phase will obviously depend on the amount of brush separation. The secondary current, which is common to both lap and stator windings, has a transformation ratio of effective primary turns to the vector sum of effective stator winding turns and effective lap winding turns. For symmetrical brush positions, the vector sum will

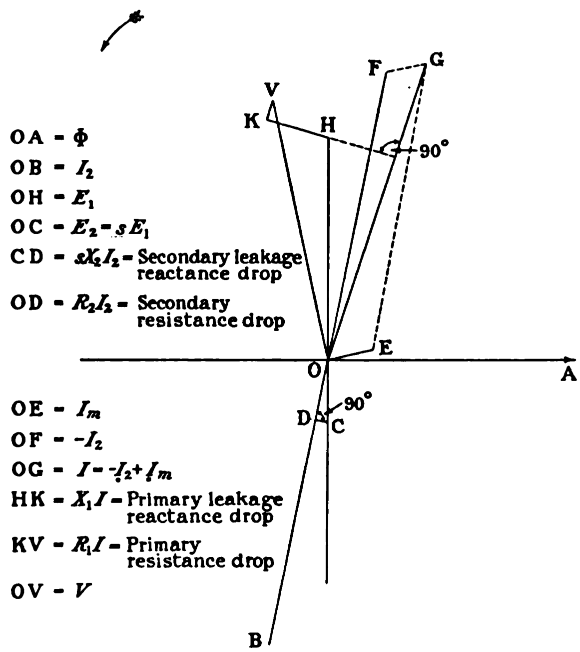

FIG. 2.—Induction motor vector diagram.

be identical with the algebraic sum. This ratio is also dependent on the brush separation; it will be high at sub-synchronous speeds, since the stator winding turns and lap winding turns oppose each other, and will be low at super-synchronous speeds, since they act together. In drawing the vector diagram for this motor it is assumed that the ratio of effective primary turns to effective stator winding turns is unity, but it should be noted that this will not make the secondary vector diagram identical with the reduced secondary vector diagram. If in an actual case this ratio is not unity, then all the vectors in the secondary diagram, as drawn, must be transformed by means of this ratio to get the true values, as in the case of the induction motor. In solving the diagram it must now be remembered that the lap E.M.F. vector and the secondary current vector are not reduced to their primary values; but this difficulty may be overcome by a very simple artifice. Two new ratios are required for this. The first ratio, which may be called the lap winding ratio (denoted in this paper by n), is the ratio of effective lap winding turns, when the brushes are separated the maximum amount, i.e. 180 electrical degrees, to effective stator winding turns. This is a constant for a given machine. The second ratio is the ratio of effective lap winding turns for an angle of brush separation of β electrical degrees to the effective lap winding turns for maximum brush separation (denoted by a in this paper). This is an independent variable, depending on the brush position.*

Fig. 3 shows the variation of a with the brush separation. In order to reduce the lap E.M.F. vector to the primary circuit it must be multiplied by $1/(an)$, and in order to reduce the secondary current vector to the primary circuit it must be multiplied by $(1 \pm an)$. It is thus seen that n and a are not used separately, and the only advantage in keeping them separate is that, whereas n may be different in different machines, and is therefore a detail of design, a can always be varied between 0 and ± 1, for any machine.† In the vector

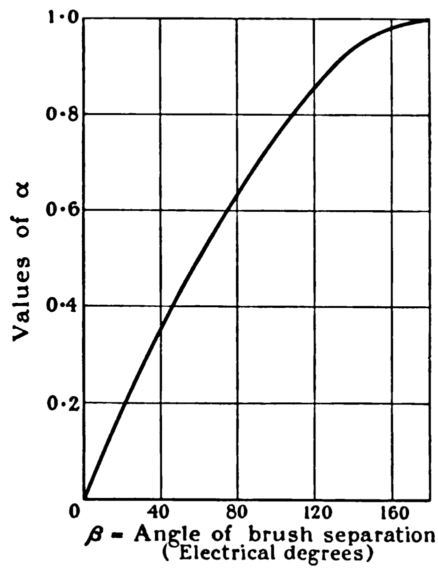

FIG. 3.—Relation between a and angle of brush separation.

diagram, the lap E.M.F. vector and the secondary current vector are drawn in the secondary diagram and reduced to the primary diagram.

The treatment is slightly more complicated when the brush positions are unsymmetrical, but it is explained in the section dealing with unsymmetrical brush positions.

THE CIRCLE DIAGRAMS WITH SYMMETRICAL BRUSH POSITIONS.

The following assumptions are made in Dr. Teago's paper and are retained in the present paper:—

(1) All currents and voltages vary harmonically with time.

(2) The rotating wave of flux is distributed round the rotor circumference according to a sine law.

(3) There is no leakage between the primary winding and the lap winding. These two windings are located in the same slots and it is reasonable to think that the

* Schrage in his paper combines these two ratios in one, but Dr. Teago uses a in the sense defined above, and it was thought better to retain his definition.

† Definitions of signs are given later.

leakage between them must be very small. In order to simplify the diagram, this assumption is subsequently further modified.

(4) The secondary leakage reactance drop is proportional to the product of the stator ampere-turns and the slip. Slip is defined as: (synchronous speed — actual speed)/synchronous speed, synchronous speed being that rotor speed which causes the primary magnetic field to become stationary with respect to the secondary (stator) winding.

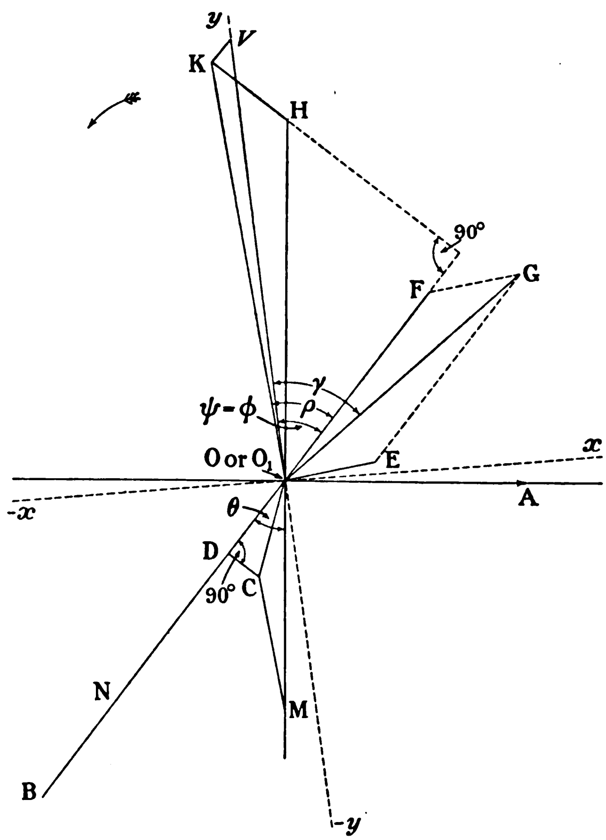

FIG. 4.—Three-phase shunt commutator motor vector diagram with symmetrical brush position.

OA = Φ.
OB = I_2 (proportional to stator ampere-turns).
BN = pI_2 (proportional to lap ampere-turns).
ON = $I_2 - pI_2$ = primary value of I_2.
OE = I_m.
OF = $-[I_2 - pI_2] = I_1$.
OG = $\dot{\text{OF}} + \dot{\text{OE}} = \dot{I}_1 + \dot{I}_m = I$ (vectorial addition).
OH = E_1.
HK = $X_1 I_2$ = primary reactance drop.
KV = $R_1 I_1$ = primary resistance drop.
OV = V.
MC = aE_L = lap E.M.F.
OK = $\frac{E_L}{n} = \frac{MC}{an}$ = primary value of lap E.M.F.
OM = $E_2 = sE_1$.
OC = resultant secondary voltage.
CD = sX_2I_2 = secondary leakage reactance drop.
OD = R_2I_2 = secondary resistance drop.
$\angle$MOD = θ; $\angle$ 180° − VOB = ψ; $\angle$ VOF = ϕ $\angle$VOG = γ; $\angle$KOF = ρ.
(For symmetrical brush positions, $\psi = \phi$.)

(5) The R.M.S. magnetizing current is constant in value.

It follows from the third assumption that the primary leakage reactance drop is proportional to the vector sum of the primary and lap ampere-turns. In order to simplify the mathematical solution of the vector diagram, this assumption is further modified by regarding the magnetizing current as flowing in a coil in parallel with the motor, and neglecting the resistance and leakage reactance drops due to it, as is done in the case of the induction motor. This is justifiable from a practical point of view since the errors involved are more than counterbalanced by the gain in simplicity, and the value of a strictly accurate method is destroyed by the uncertainty of the data of the motor. With this assumption the primary leakage reactance drop is proportional to the stator ampere-turns, since these are equal and opposite to the vector sum of the primary and lap ampere-turns. Fig. 4 shows the vector diagram based on these assumptions.

It is also assumed that $n_{e1} = n_{e2}$, and appropriate values are given to the secondary vectors in accordance with this assumption (see page 1140).

The following quantities are assumed to be constant: X_1, X_2, R_1, R_2, V, n, and the supply frequency.

Also, let $(X_1 + X_2) = X$.

In order that one mathematical solution may serve for sub-synchronous and super-synchronous speeds, the following conventions as to signs will be adopted.

s = slip. This is positive below synchronous speed and is negative above synchronous speed.

a is positive when the angle of brush separation is such that the stator and lap ampere-turns oppose each other, and is negative when the angle of brush separation is such that the stator and lap ampere-turns act in the same direction.

It should be noted that although a varies as the brushes are moved, it is an independent variable which may be kept constant at will. In the solution of the diagram it is assumed constant, but of course any value between -1 and $+1$ may be assigned to it for a particular solution.

Since n is a constant, it follows that p changes sign with a.

EQUATIONS FOR CIRCLE DIAGRAMS.

It should be noted that the diameter of the secondary circle will vary relatively to the diameter of the primary circle when the brush position is altered.

From Fig. 4 we get

$$sE_1 = I_2R_2 \cos\theta + sI_2X_2 \sin\theta + aE_L \cos(\rho - \theta) \quad (1)$$

$$s = \frac{I_2R_2 \sin\theta - aE_L \sin(\rho - \theta)}{I_2X_2 \cos\theta} \quad . \quad . \quad (2)$$

$$(E_L/n) \sin(\rho - \theta) = X_1I_2 \cos\theta \quad . \quad . \quad (3)$$

$$(E_L/n) \cos(\rho - \theta) = E_1 + X_1I_2 \sin\theta \quad . \quad (4)$$

From equations (2) and (3) we obtain

$$s = \frac{R_2}{X_2} \tan\theta - p\frac{X_1}{X_2} \text{ (where } p = an) \quad . \quad . \quad (5)$$

From equations (1), (4) and (5),

$$E_1 = \frac{I_2R_2X_2}{\{R_2 \sin\theta - pX \cos\theta\}} \text{ [where } X = X_1 + X_2]$$

$$\cos\theta = \frac{V\cos\psi - R_1I_1}{E_1}; \quad \sin\theta = \frac{V \sin\psi - X_1I_2}{E_1}$$

$$\therefore I_2 = \frac{V}{X}\left\{\frac{R_2 \sin\psi - pX\cos\psi}{R_2 - p(1-p)R_1}\right\} \quad . \quad . \quad (6)$$

Transforming equation (6) to Cartesian co-ordinates, with O_1 as origin and $O_1V_1 = V$ as the axis of y (see Fig. 4),

$$\text{let}\quad \left\{\begin{matrix} -I_2 \sin\psi = x \quad \text{and} \quad I_1 \sin\psi = x_1 \\ -I_2 \cos\psi = y \quad \text{and} \quad I_1 \cos\psi = y_1 \end{matrix}\right\}$$

[I_1 and I_2 are assumed to be positive.]

Then

$$\left[x + \frac{VR_2}{2X\,\{R_2 - p(1-p)R_1\}}\right]^2 + \left[y - \frac{Vp}{2\{R_2 - p(1-p)R_1\}}\right]^2 = \frac{V^2\left\{\left(\frac{R_2}{X}\right)^2 + p^2\right\}}{4\{R_2 - p(1-p)R_1\}^2}$$

which is the equation of a circle, with centre at (a, b) and radius r,

$$\text{where}\quad a = -\frac{VR_2}{2X\{R_2 - p(1-p)R_1\}}$$

$$b = \frac{Vp}{2\{R_2 - p(1-p)R_1\}}$$

$$r = \left[\frac{VR_2}{2\{R_2 - p(1-p)R_1\}}\right]\left[\frac{1}{X^2} + \left(\frac{p}{R_2}\right)^2\right]^{\frac{1}{2}}$$

Since $I_1 = -I_2(1-p)$ in magnitude and direction, therefore, the free end of the vector I_1 travels round a circle, the centre of which is (a_1, b_1) and radius r_1.

$$a_1 = -a(1-p) = \frac{VR_2(1-p)}{2X\{R_2 - p(1-p)R_1\}}$$

$$b_1 = -b(1-p) = \frac{-Vp(1-p)}{2\{R_2 - p(1-p)R_1\}}$$

$$r_1 = r(1-p) = \left[\frac{VR_2(1-p)}{2\{R_2 - p(1-p)R_1\}}\right]\left[\frac{1}{X^2} + \left(\frac{p}{R_2}\right)^2\right]^{\frac{1}{2}}$$

If the origin is displaced by an amount equal to the magnetizing current in magnitude and opposite in direction, the I_1 circle becomes the I circle or supply current circle, and the power factor at any point may be determined by measuring the angle which the I vector to that point makes with OV, where O is the new origin, and OV the new axis of y.

If $p = 0$, the case corresponds to that of an induction motor, and

$$a_1 = -a = \frac{V}{2X};\quad b_1 = -b = 0$$

$$r_1 = r = \frac{V}{2X}$$

Sources of Error in the Preceding Theory.

The theory is subject to all the errors which occur in the theory of the simple induction motor. In actual machines, fluxes, voltages and currents do not vary harmonically. The amount of error involved cannot be easily determined, but probably this will not be serious up to full load, although considerable distortion of the circle diagram will probably occur at heavy overloads.

The assumption of constant primary reactance involves another error. In this theory the primary leakage is assumed to be produced by the primary and lap ampere-turns. As the number of turns in the lap winding depends on the brush position the primary reactance will also be dependent on this.

The most serious source of error occurs in assuming the secondary resistance to be constant. This was found to be so serious that a partial correction has been made in the circles drawn, but as the resistance

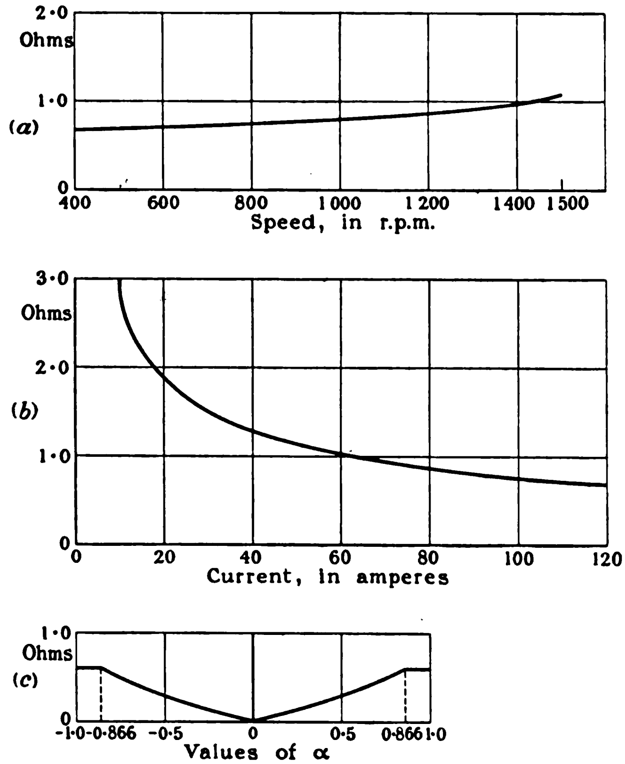

FIG. 5.—Secondary resistance (in terms of the primary), Stator resistance = 0·5 ohm.

(a) Relation between brush contact resistance and speed. Constant current = 86 amperes.
(b) Relation between brush contact resistance and current. Constant speed = 1 000 r.p.m.
(c) Relation between lap winding resistance and α.

varies with current it was not possible to make a complete correction.

The secondary resistance may be divided into three parts, the stator winding resistance, the brush contact drop, and the lap winding resistance. The stator resistance in the machine tested was found to be 0·5 ohm (in terms of the primary) and this is fairly constant, the only variation being due to eddy currents which depend on the frequency of the secondary current. The brush contact drop is shown by Fig. 5 [(a) and (b)]. It varies both with current and with speed. The lap winding resistance per phase depends on the number of turns included. When the angle of brush separation exceeds 120°, the apparent lap winding resistance per phase does not increase any further as the currents of different phases flowing in the same conductors par-

tially cancel out. The apparent resistance of the lap winding per phase is shown in Fig. 5 (c) on the assumption that all three phases are carrying currents.

In drawing the theoretical circle diagrams the value of secondary resistance used has been chosen for full-

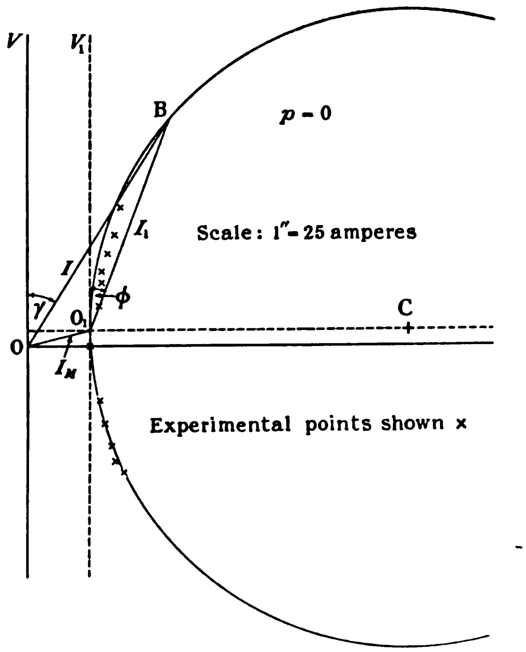

FIG. 6.

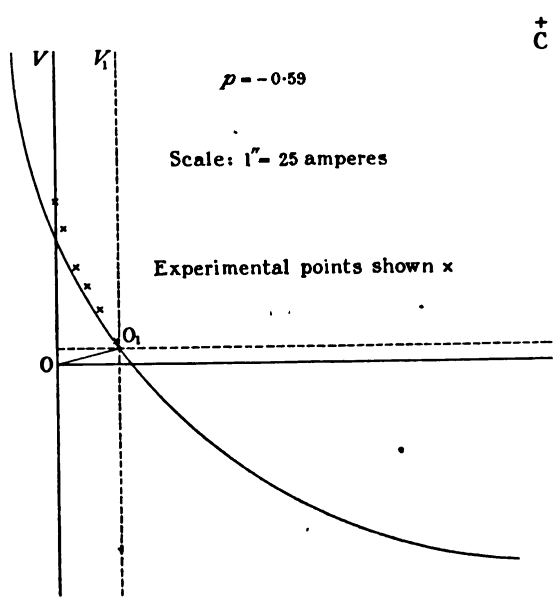

FIG. 7.

load current. It follows, therefore, that the value will be incorrect for all other currents.

Test-results, obtained at a reduced voltage, showed considerable distortion of the circle diagram at heavy overloads up to standstill, and this was no doubt mainly due to the change in the secondary resistance, although the other errors mentioned would also contribute their effects.

The brush contact resistance was found to be negligible in the primary resistance, owing to the much higher resistance of the windings.

THE THEORETICAL CIRCLE DIAGRAMS FOR THE MOTOR TESTED.

The motor tested was the same one as that on which Dr. Teago carried out his experiments. The following

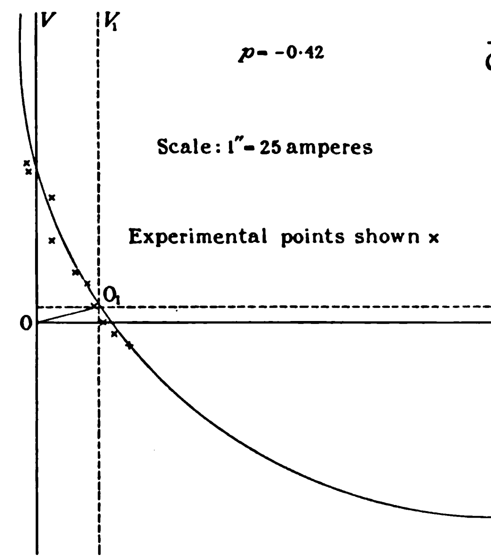

FIG. 8.

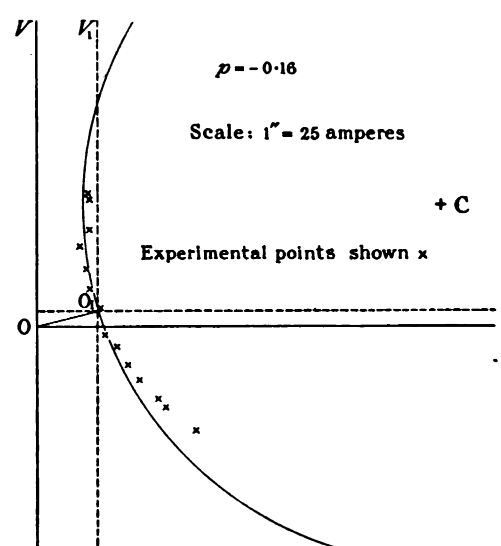

FIG. 9.

particulars of the machine were used in determining the theoretical circle diagrams.

Primary volts = 400 (phase voltage = 230).
Full-load secondary current = 86 amperes.

No-load current (magnetizing current) = 8 amperes at 0·2 power factor.

(This value was the mean of a number, measured experimentally, over the whole speed range of the motor.)

Synchronous speed = 1 000 r.p.m.

Turns per phase in primary winding = 288 = n_1.

Breadth factor of primary winding = 0·96 = k_{w1}.

Turns per phase in stator winding = 60 = n_2.

Breadth factor of stator winding = 0·83 = k_{w2}.

Transformation ratio (a = 0) $= \dfrac{288 \times 0\cdot 96}{60 \times 0\cdot 83} = 5\cdot 55$.

Turns per phase in lap winding for a brush separation of 180 electrical degrees = 54 = n_l.

Breadth factor of lap winding for a brush separation of 180 electrical degrees = 0·55 = k_{wl}.

(This low value was due to the coils being short-pitched.)

$$n = \frac{54 \times 0\cdot 55}{60 \times 0\cdot 83} = 0\cdot 6 \text{ and } p = an = 0\cdot 6a.$$

Primary resistance = R_1 = 0·42 ohm.

Secondary resistance = R_2 (see Fig. 5).

Primary and secondary reactance = $X_1 + X_2 = X$ = 2·8 ohms.

The values of R_1, R_2 and X were determined experimentally and are all reduced to the primary.

From these particulars the positions of the centres and the diameters of the circles for seven values of a have been calculated. These are shown in Table 1, and the circles are drawn in Figs. 6–12. The value of R_2 used in each case was obtained from the curves in Fig. 5 for full-load secondary current.

a_1 and b_1 are measured from O_1. OO_1 = the no-load current.

TABLE 1.

a	p	Full-load speed (motoring)	a_1	b_1	r_1	Value of R_2 used in each case
		r.p.m.	amps.	amps.	amps.	ohms
−0·98	−0·59	1 500	56	41	69	2·2
−0·70	−0·42	1 300	51	34	61	1·8
−0·27	−0·16	1 100	45	14	47	1·5
0	0	950	41	0	41	1·3
0·27	0·16	800	36	−11	37	1·5
0·70	0·42	500	25	−16	30	1·8
0·95	0·57	300	19	−17	25	1·8

The actual calculations involved are given below for one case. The other six were worked out similarly.

Case I. $a = -0\cdot 98$.

$p = 0\cdot 6a = -0\cdot 59$; $R_2 = 2\cdot 2$ ohms.

$V = 230$ volts; $X = 2\cdot 8$ ohms; $R_1 = 0\cdot 42$ ohm.

From the equations on page 1143 :—

TEST-RESULTS.

A large number of test-points were obtained for the seven brush positions, of which the theoretical circle diagrams have been worked out. These are plotted in Figs. 6–12, and their agreement with the theoretical circles may be seen to be reasonably close.

The most serious discrepancies occur when $p = 0\cdot 42$ (see Fig. 11). Here the agreement is good for motoring, but the generation is unexpectedly poor. Experiments carried out at a quarter of the standard voltage confirmed this result for points further round the circle, and so far it has been found impossible to assign any

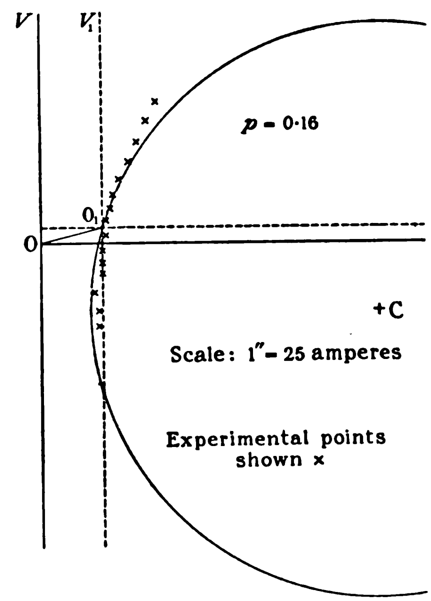

FIG. 10.

satisfactory reasons for it. It is hoped that further work on this motor may reveal the cause. All the other circles, when obtained at a quarter of the standard voltage, were very much distorted. It is believed that this distortion is mainly due to the change in the secondary resistance. The object of obtaining points at a quarter voltage was to find the shape of the circle diagram beyond the normal working range of the motor.

A certain amount of error was caused by the angles between half brushes not being the same for all three phases, due to faulty setting in erecting the motor. Although this caused considerable out-of-balance currents in the secondary windings, the primary currents were balanced.* These out-of-balance currents would increase the copper losses and would possibly be respon-

* See also F. J. TEAGO, *loc. cit.*, p. 334, Table 1.

$$a_1 = \frac{VR_2(1-p)}{2X\{R_2 - p(1-p)R_1\}} = \frac{230 \times 2\cdot 2 \times 1\cdot 59}{5\cdot 6\{2\cdot 2 + (0\cdot 59 \times 1\cdot 59 \times 0\cdot 42)\}} = \frac{805}{5\cdot 6 \times 2\cdot 59} = 56 \text{ amperes.}$$

$$b_1 = \frac{-Vp(1-p)}{2\{R_2 - p(1-p)R_1\}} = \frac{230 \times 0\cdot 59 \times 1\cdot 59}{2 \times 2\cdot 59} = 41 \text{ amperes.}$$

$$r_1 = \left[\frac{VR_2(1-p)}{2\{R_2 - p(1-p)R_1\}}\right]\left[\frac{1}{X^2} + \left(\frac{p}{R_2}\right)^2\right]^{\frac{1}{2}} = \left[\frac{230 \times 2\cdot 2 \times 1\cdot 59}{2 \times 2\cdot 59}\right]\left[\frac{1}{(2\cdot 8)^2} + \left(\frac{0\cdot 59}{2\cdot 2}\right)^2\right]^{\frac{1}{2}} = 69 \text{ amperes.}$$

sible for part of the discrepancies between test-results and the theoretical curves.

Figs. 6–12 show theoretical circle diagrams (with symmetrical brush positions); line voltage = 400 (phase voltage = 230), frequency = 50 cycles per sec.

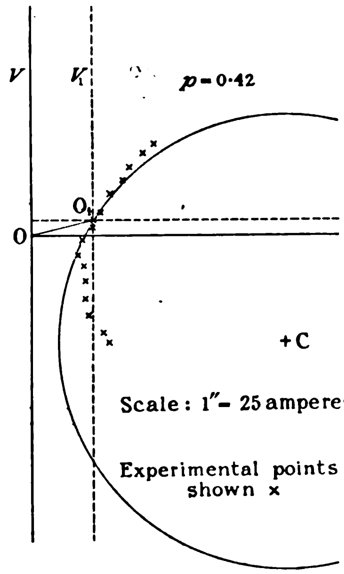

FIG. 11.

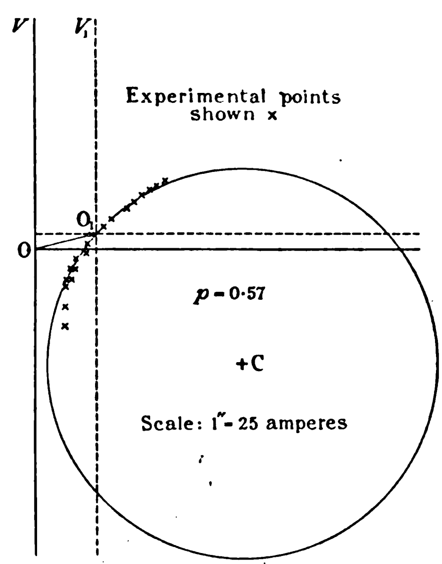

FIG. 12.

In these figures :—

OO_1 = no-load (magnetizing) current.
$O_1B = I_1$.
$OB = I$ = primary current.
$VOB = \gamma$ = angle of lag of primary current.
a_1 and b_1 are the co-ordinates of C with respect to O_1 as origin.

RELATION BETWEEN SECONDARY CURRENT AND SLIP, AND RELATION BETWEEN TORQUE, MECHANICAL POWER AND SLIP, WITH SYMMETRICAL BRUSH POSITIONS.

By eliminating ψ and retaining s in equations (1) to (6) on page 1142, the following equations may be obtained:—

$$I_2 = \frac{(s-p)V}{\sqrt{[s^2X^2 + \{R_2 + (1-p)(s-p)R_1\}^2]}}$$

Mechanical power

$$= P = I_2^2 R_2 \left\{\frac{1-s}{s-p}\right\}$$

$$= \frac{(1-s)(s-p)V^2R_2}{[s^2X^2 + \{R_2 + (1-p)(s-p)R_1\}^2]}$$

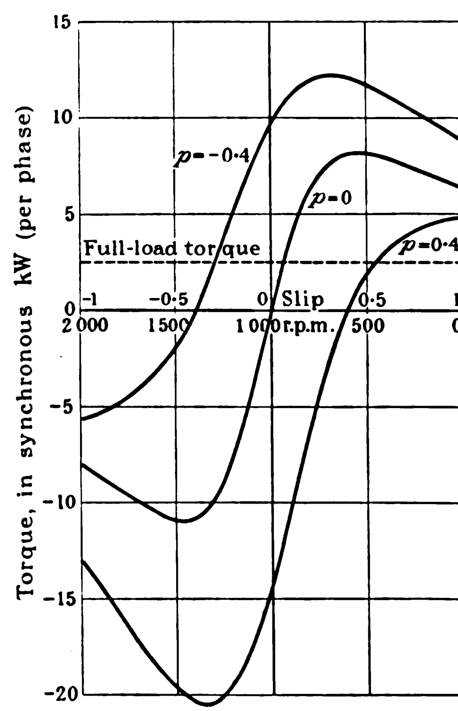

FIG. 13.—Theoretical torque/speed curves.

The mechanical or shaft power is the output when motoring, and the input when generating. Both it and the shaft torque are positive in these equations when the machine is motoring, and negative when the machine is generating.

Electrical power is the input when motoring, and the output when generating.

$$\text{Torque} = T = \frac{(s-p)V^2R_2}{[s^2X^2 + \{R_2 + (1-p)(s-p)R_1\}^2]}$$

synchronous watts.

By differentiating, the expression for maximum torque may be obtained,

$$T_m = \frac{\pm \frac{1}{2} R_2 V^2}{+\sqrt{[\{R_1^2(1-p)^2 + X^2\}\{p^2X^2 + R_2^2\}]} \pm \{pX^2 + R_2R_1(1-p)\}}$$

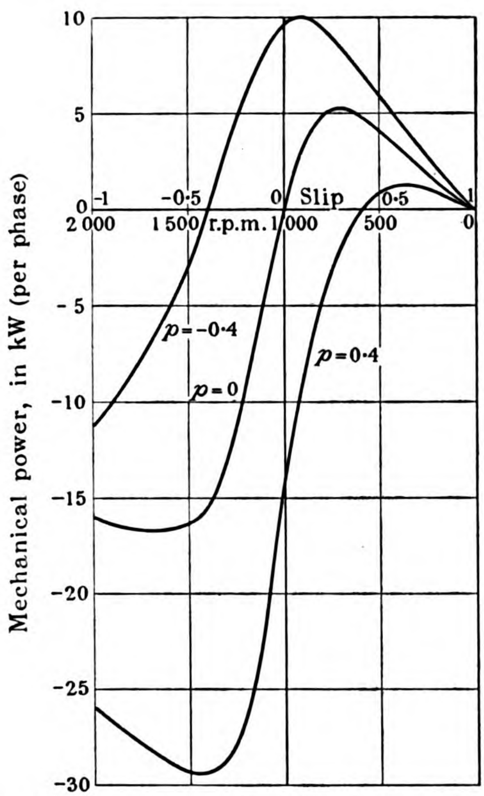

FIG. 14.—Theoretical mechanical-power/speed curves.

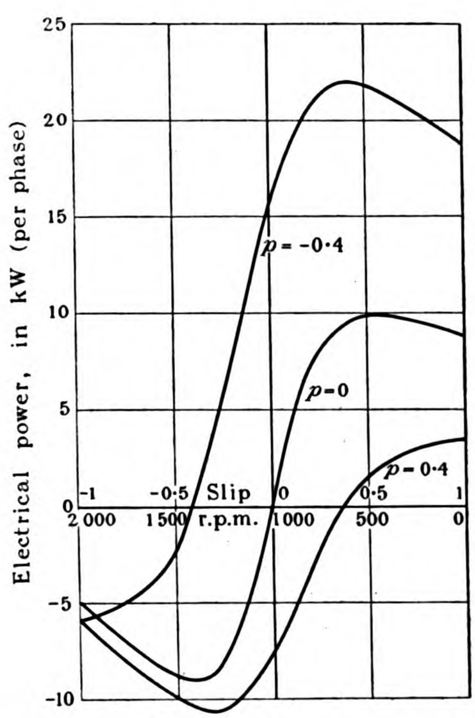

FIG. 15.—Theoretical electrical-power/speed curves.

Slip for maximum torque

$$s_m = p \pm \sqrt{\left[\frac{R_2^2 + p^2X^2}{R_1^2(1-p)^2 + X^2}\right]}$$

Where two signs are given, the top one refers to the motoring zone, and the lower one to the generating zone.

If $p = 0$, these equations reduce to the induction motor case.

$$I_2 = \frac{sV}{\sqrt{[s^2X^2 + \{R_2 + sR_1\}^2]}}$$

$$T = \frac{sV^2R_2}{[s^2X^2 + (R_2 + sR_1)^2]}$$

$$T_m = \frac{\pm V^2}{2[+\sqrt{\{R_1^2 + X^2\}} \pm R_1]}$$

$$s_m = \frac{\pm R_2}{+\sqrt{[R_1^2 + X^2]}}$$

Lack of time prevented the accurate verification of these formulæ by test-results. The theoretical curves for the motor tested are shown in Figs. 13–15, and the test-results obtained indicated the general shape to be correct. Test-curves obtained by the A.S.E.A. Co. also showed a similarity to these theoretical curves.

EFFECT OF DISPLACING THE BRUSH GEAR BODILY THROUGH AN ANGLE η.

By means of unsymmetrical brush positions, considerable improvements may be effected in the performance of the motor. These are outlined later. The solution of the vector diagram will be given first. In order to simplify the treatment, the primary resistance will be neglected, and the results are therefore only approximate.

The angle η will be considered positive if it causes the injected E.M.F. to lag on the primary supply pressure, and negative if it leads on the primary supply pressure.

The vector diagram is given in Fig. 16, the lettering being the same as for Fig. 4. Note that K and V coincide as a result of assuming the primary resistance to be negligible.

The injected E.M.F. will now lag behind the primary supply pressure by the angle η. The lap ampere-turns have a space advance of η over the stator ampere-turns and this is shown in Fig. 16 by an equivalent time-phase advancement. The following equations may now be derived from Fig. 16 :—

$$V = \frac{E_L}{n}$$

$$\cos\theta = \frac{V}{E_1}\cos\psi\,; \quad \sin\theta = \frac{V\sin\psi - X_1I_2}{E_1}$$

$$s = \frac{I_2R_2\sin\theta - aE_L\sin\{(\psi-\eta)-\theta\}}{I_2X_2\cos\theta}$$

$$sE_1 = I_2R_2\cos\theta + sX_2I_2\sin\theta + aE_L\cos\{(\psi-\eta)-\theta\}$$

From these equations it may be proved that :—

$$I_2^2R_2X + I_2V\{pX\cos(\psi-\eta) - R_2\sin\psi\} - pV^2\sin\eta = 0$$

which is the equation of a circle.

Transforming to Cartesian co-ordinates with O_1 as origin and O_1V_1 as axis O_1y

$$-I_2 \sin\psi = x \quad \text{and} \quad I_1 \sin\phi = x_1$$
$$-I_2 \cos\psi = y \quad \text{and} \quad I_1 \cos\phi = y_1$$

$$\left\{x + \tfrac{1}{2}V\left(\frac{1}{X} - \frac{p \sin\eta}{R_2}\right)\right\}^2 + \left\{y - \frac{pV\cos\eta}{2R_2}\right\}^2 = \frac{V^2}{4}\left\{\frac{p^2}{R_2^2} + \frac{2p\sin\eta}{R_2X} + \frac{1}{X^2}\right\}$$

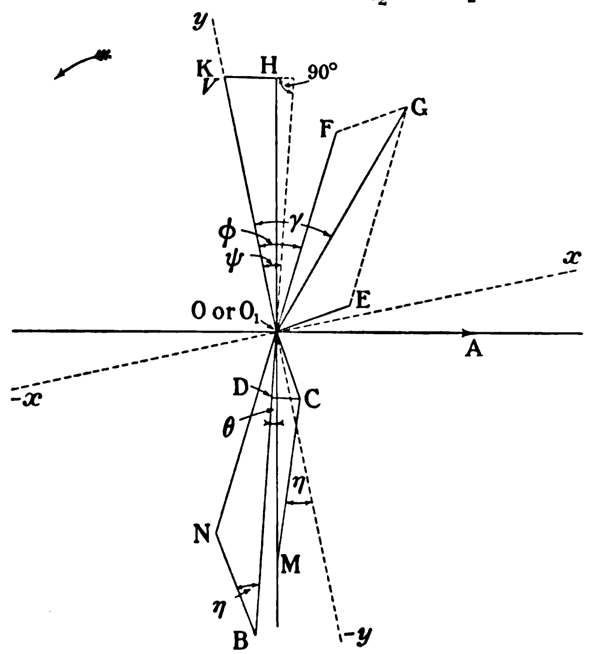

FIG. 16.—Vector diagram with unsymmetrical brush position.

This is the circle diagram equation of the secondary current.

$$\text{Centre}\begin{cases} a = -\tfrac{1}{2}V\left(\dfrac{1}{X} - \dfrac{p\sin\eta}{R_2}\right) \\ b = \tfrac{1}{2}V\left(\dfrac{p\cos\eta}{R_2}\right) \end{cases}$$

$$\text{Radius} = r = \tfrac{1}{2}V\sqrt{\left[\frac{p^2}{R_2^2} + \frac{2p\sin\eta}{R_2X} + \frac{1}{X^2}\right]}$$

$$x_1 = I_1\sin\phi = I_2\sin\psi - pI_2\sin(\psi - \eta)$$
$$y_1 = I_1\cos\phi = I_2\cos\psi - pI_2\cos(\psi - \eta)$$

$$\therefore x_1^2 + y_1^2 + x_1\left\{V\left(\frac{p\sin\eta}{R_2} + \frac{p\cos\eta}{X} - \frac{1}{X}\right)\right\} + y_1\left\{V\left(\frac{p\sin\eta}{X} + \frac{p\cos\eta}{R_2} - \frac{p^2}{R_2}\right)\right\} = \frac{pV^2\sin\eta(1 - 2p\cos\eta + p^2)}{R_2X}$$

This is the circle diagram equation of I_1

$$\text{Centre}\begin{cases} a_1 = \tfrac{1}{2}V\left\{\dfrac{1}{X} - p\left(\dfrac{\sin\eta}{R_2} + \dfrac{\cos\eta}{X}\right)\right\} \\ b_1 = -\tfrac{1}{2}V\left\{p\left(\dfrac{\sin\eta}{X} + \dfrac{\cos\eta}{R_2}\right) - \dfrac{p^2}{R_2}\right\} \end{cases}$$

$$\text{Radius} = r_1 = \tfrac{1}{2}V\sqrt{\left[(1 - 2p\cos\eta + p^2)\left\{\frac{1}{X^2} + \frac{p^2}{R_2^2} + \frac{2p\sin\eta}{R_2X}\right\}\right]}$$

This circle is identical with the primary current circle, if the origin be displaced by an amount equal to the magnetizing current and opposite in direction. If η does not exceed about 15° it may be assumed that $\sin\eta = \eta$ and $\cos\eta = 1$. Then :—

$$a_1 = \left\{\frac{V}{2X}(1 - p) - \frac{\eta pV}{2R_2}\right\}$$
$$b_1 = -\left\{\frac{Vp}{2R_2}(1 - p) + \frac{\eta pV}{2X}\right\}$$
$$r_1 = \tfrac{1}{2}V(1 - p)\sqrt{\left[\frac{1}{X^2} + \frac{p^2}{R_2^2} + \frac{2p\eta}{R_2X}\right]}$$

In this form it is easy to see the effect of η, since those terms containing η disappear when $\eta = 0$.

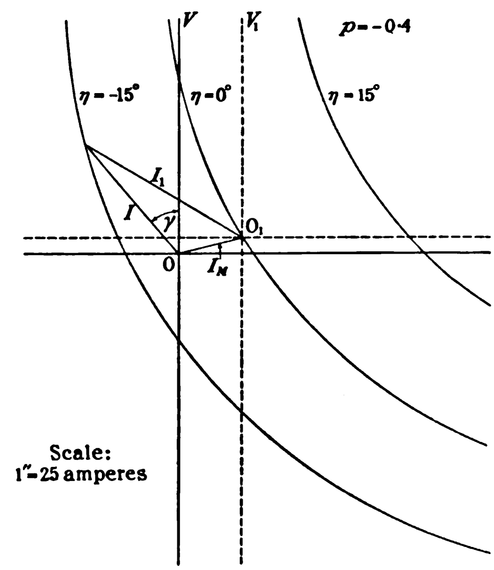

FIG. 17.—Theoretical circle diagrams.

Brush gear displaced by the angle η. Super-synchronous speed. $p = -0 \cdot 4$; line voltage = 400; frequency = 50 cycles per sec.

It is interesting to note that if $p = 0$ the η terms disappear, thus showing that an unsymmetrical brush position has no effect on the circle diagram, for zero brush separation. This is, of course, what one would expect.

In Figs. 17 and 18 the theoretical circles for the motor tested are drawn with $\eta = 15°$, 0° and $-15°$ for both sub-synchronous speed and super-synchronous speed. The general trend of these curves was verified experimentally, but lack of time prevented the careful verification of them.

From these it may be seen that at sub-synchronous speeds a positive angle η advances the time phase of the primary current relative to the supply voltage OV, while at super-synchronous speeds a negative angle η has the same effect.

Expressions for the torque, mechanical power and slip are not reproduced as the mathematics involved is very cumbersome, but the general effect on the performance may easily be arrived at by the following line of argument. The effect of displacing the brush

gear is to cause the injected E.M.F. to alter its phase, and this in turn alters the phase of the resultant secondary E.M.F. and the secondary current.

At sub-synchronous speeds the secondary current is lagging behind the flux with symmetrical brush position (Fig. 4), and a positive angle η will bring it into phase with the flux. It will then have a minimum value for a given torque so that the efficiency will be higher than with the symmetrical setting, while the maximum torque will be increased considerably. The power factor of the primary current will also be considerably improved, although not to unity power factor. If improvement to unity power factor is desired, η must be increased still further, so that the secondary current leads on the flux. By this means the secondary current may be made to supply the magnetizing component.

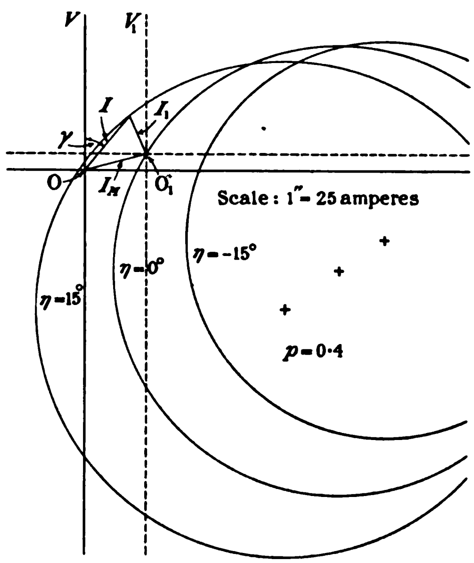

FIG. 18.—Theoretical circle diagrams.

Brush gear displaced by the angle η. Sub-synchronous speed. $p = -0\cdot4$; line voltage = 400 ; frequency = 50 cycles per sec.

As the stator and lap ampere-turns are opposed to each other at sub-synchronous speeds the effective turns will be small, and the secondary current will have to lead by a large amount in order to supply the magnetizing component. This will involve, for a given torque, an increased secondary current and, therefore, a lower efficiency. It is not, therefore, advisable to improve the power factor at sub-synchronous speeds much beyond that point at which the secondary current begins to lead on the flux.

In most machines the power factor may be brought up to 0·8, even at the lowest speeds, without much loss of efficiency.

At super-synchronous speeds the secondary current is generally leading the flux with symmetrical brush position, and the motor therefore operates near unity power factor.

The power factor may be brought actually to unity without much loss of efficiency, as the stator and lap ampere-turns act together, and therefore a comparatively small lead of the secondary current on the flux will supply the magnetizing component. Alternatively, the maximum torque and the efficiency may be raised by bringing the secondary current into phase with the flux. There is not much advantage to be gained by this, as the maximum torque is already high at super-synchronous speeds.

It should be noted that at sub-synchronous speeds maximum efficiency will occur practically when the secondary current is in phase with the flux, since the primary copper losses are small. At super-synchronous speeds the primary copper losses are greater, and the secondary current may have a correspondingly greater lead on the flux for maximum efficiency. Although in most machines unity power factor operation will entail a slight drop from maximum efficiency at super-synchronous speeds, it will be negligible for practical purposes.

Thus by suitable brush movements the performance of the motor may be improved at all speeds. By unsymmetrical gearing the double movement may be obtained by moving one wheel, and this has the advantage that the makers fix the setting; but to get the best performance under all conditions it is necessary to have two wheels, one to separate the half-brushes and the other to displace the gear bodily.

Generation.

It is well known that the lower half of the circle diagram of the induction motor represents a generating zone, and generation is obtained by driving the motor above synchronous speed.

In the three-phase shunt commutator motor also, the lower portion of the circle diagram represents a generating zone, and generation takes place when the motor is driven above the speed at which, for a given brush position, it would operate as a motor. By choosing a suitable brush position, therefore, generation may be obtained for a large range of speed, and the amount of generation may be controlled within wide limits.

The circle diagrams in Figs. 6–12 and the performance curves in Fig. 15 for symmetrical brush positions, indicate that for all positive values of p the amount of generation may be varied up to approximately the same maximum, although the power factor improves considerably as p increases. When p becomes negative the maximum generation falls off slowly, while the power factor of generation falls off very rapidly as p increases negatively.

The circles in Fig. 17 show, however, that even for large negative values of p regeneration at unity power factor may be obtained by displacing the brush gear bodily, and in this case the magnetizing current can be supplied by the secondary for a lower copper loss, since the lap and stator ampere-turns act together, and the fall in efficiency is small and may be non-existent or even negative.

Generation may, therefore, be obtained at all speeds above a certain minimum speed, at unity power factor, high efficiency, and controllable as to amount.

Conclusions.

A study of this paper will show that the three-phase shunt commutator motor is capable of operating either

as a motor or a generator at unity power factor and high efficiency over a speed range of about 3 to 1. This speed range may be increased further by special design and by a sacrifice of output. It has a starting torque of twice full-load torque with a starting current of only $1\frac{1}{2}$ times full-load current in the primary circuit and twice full-load current in the secondary circuit. No starting gear is required, except a three-pole switch. Its chief limitation, as already pointed out in Dr. Teago's paper, is commutation, and this prevents motors of very large sizes being built.

It is hoped that the theory put forward in this paper will be easier to understand and apply than Schrage's owing to the elimination of advanced mathematics; while the divergencies of test-results from theory are pointed out, and some of the possible causes suggested. The author regrets that he was unable to verify more fully the torque/speed and power/speed curves, and also the circle diagrams with unsymmetrical brush positions. The results are put forward, however, in the hope that they may provide a starting point for other investigators.

Thanks are due to the Faculty of Engineering and Prof. E. W. Marchant for permission to publish the results, and also to Dr. Teago for his valuable help and advice, both in the experimental work and in the preparation of the paper.

APPENDIX.

List of Symbols and Notation Used in the Appendix.

Total number of conductors in lap (secondary) winding $= z$.

Current in phase 1 of secondary winding $= i_1$.
Current in phase 2 of secondary winding $= i_2$.
Current in phase 3 of secondary winding $= i_3$.
Current in any conductor $= i$.
Angle between half brushes in phase 1 $= \psi_1$.
Angle between half brushes in phase 2 $= \psi_2$.
Angle between half brushes in phase 3 $= \psi_3$.
Where no particular phase is referred to, and ψ_1, ψ_2, and ψ_3 are assumed equal, the letter ψ without suffix is used.

Let $\eta_2 = \psi_1 - \psi_2$
and $\eta_3 = \psi_1 - \psi_3$

η_2 and η_3 are angles of error in the angles between half brushes.

Let the maximum rate of cutting flux by a conductor $= \Phi$ lines per sec.

Let $E_1 =$ injected E.M.F. in phase 1.
$E_2 =$ injected E.M.F. in phase 2.
$E_3 =$ injected E.M.F. in phase 3.
$\theta =$ angle between any conductor and the axis of maximum flux (i.e. NO in Fig. 19 = axis of maximum flux).
$\beta_1 =$ angle between centre line of brush gear of phase 1 and the axis of maximum flux.
$\beta_2 =$ angle between centre line of brush gear of phase 2 and the axis of maximum flux.
$\beta_3 =$ angle between centre line of brush gear of phase 3 and the axis of maximum flux.
$r_1 =$ combined resistance of stator and lap winding and brush contact resistance of phase 1.
$r_2 =$ combined resistance of stator and lap winding and brush contact resistance of phase 2.
$r_3 =$ combined resistance of stator and lap winding and brush contact resistance of phase 3.

All angles are in radians unless expressly stated otherwise.

Operation at Synchronous Speed.

The operation of this motor at synchronous speed is accompanied by some interesting phenomena. At this

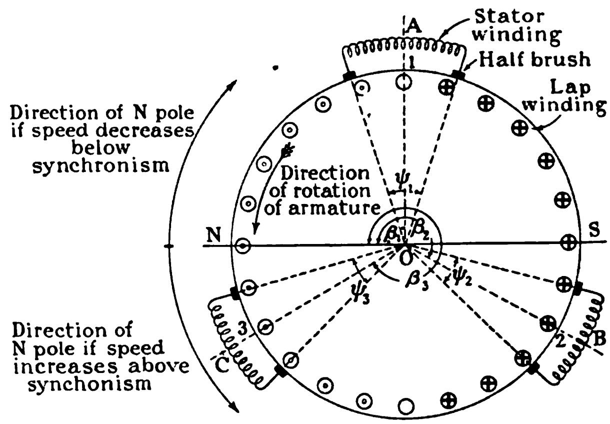

Fig. 19.—The particular case of synchronous speed.
$\angle NOA = \beta_1$; $\angle NOB = \beta_2$; $\angle NOC = \beta_3$

speed the stator winding E.M.F. is zero, and the secondary current is therefore produced entirely by the lap winding E.M.F. Moreover, since the magnetic field is now stationary in space, the secondary current will be direct current. It also follows that the secondary currents will be different in the different phases since the lap winding E.M.F.'s cannot be the same in all three phases, and their actual values will depend on the relative positions of the field and the brushes. In Fig. 19 is shown a diagram of the lap winding, from which a formula for the torque is developed.

Average rate of cutting flux by lap conductors of phase 1

$$= \frac{1}{\psi_1}\int_{\beta_1-\frac{1}{2}\psi_1}^{\beta_1+\frac{1}{2}\psi_1} \Phi \cos\theta d\theta$$

$\therefore$ injected E.M.F. in phase 1

$$= E_1 = 2\Phi \cos\beta_1 \cdot \frac{\sin \frac{1}{2}\psi_1}{\psi_1} \cdot \frac{z\psi_1}{\pi}$$

$$= \frac{2}{\pi} z\Phi \cos\beta_1 \sin \tfrac{1}{2}\psi_1$$

This assumes a breadth factor of unity. Up to full load at synchronous speed the angles ψ_1, ψ_2 and ψ_3

are all small angles, and the effect of phase difference in the E.M.F.'s of different conductors between two half brushes is negligible. It is also justifiable to assume that $\sin \frac{1}{2}\psi_1 = \frac{1}{2}\psi_1$ for the same reason.

Then $\qquad E_1 = (z\Phi\psi_1/\pi) \cos \beta_1$

and $\qquad i_1 = E_1/r_1 = z\Phi\psi_1 \cos \beta_1/(\pi r_1)$

Torque produced by phase 1 is proportional to $\Phi \cos \beta_1 \times i_1$.

$\therefore$ torque produced by phase 1 is proportional to $z\Phi^2\psi_1 \cos^2 \beta_1/(\pi r_1)$.

Similarly torque produced by phase 2 is proportional to $z\Phi^2\psi_2 \cos^2 \beta_2/(\pi r_2)$.

Similarly torque produced by phase 3 is proportional to $z\Phi^2\psi_3 \cos^2 \beta_3/(\pi r_3)$.

$\therefore$ total torque ($= T$) is proportional to

$$\frac{z\Phi^2}{\pi}\left\{\frac{\psi_1}{r_1}\cos^2 \beta_1 + \frac{\psi_2}{r_2}\cos^2 \beta_2 + \frac{\psi_3}{r_3}\cos^2 \beta_3\right\} \quad . \quad (7)$$

In the ideal machine :—

$$r_1 = r_2 = r_3 = r\,; \quad \psi_1 = \psi_2 = \psi_3 = \psi$$

and

$$\beta_2 = \beta_1 + \frac{2\pi}{3}, \quad \beta_3 = \beta_1 + \frac{4\pi}{3}$$

so that the above expression then reduces to

$$T \propto \frac{1 \cdot 5 z\Phi^2}{\pi} \cdot \frac{\psi}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

or

$$T \propto \frac{z\Phi^2}{2\pi r} \cdot 3\psi \quad . \quad . \quad . \quad . \quad . \quad . \quad (8a)$$

i.e. the torque is the same for a given brush setting, when the motor reaches synchronous speed, whatever position the field comes to rest in, but the currents in the three phases are respectively

$$\frac{z\Phi\psi}{\pi r}\cos \beta_1\,; \quad \frac{z\Phi\psi}{\pi r}\cos\left(\beta_1 + \frac{2\pi}{3}\right)$$

and

$$\frac{z\Phi\psi}{\pi r}\cos\left(\beta_1 + \frac{4\pi}{3}\right)$$

and the torques produced are proportional to $\Phi^2 \cos^2 \beta_1$, $\Phi^2 \cos^2 \{\beta_1 + (2\pi/3)\}$ and $\Phi^2 \cos^2 \{\beta_1 + (4\pi/3)\}$. Both the current and the torque of any one phase are therefore dependent on the position of the brushes of that phase relative to the magnetic field. From this investigation it would appear that as the total torque is uniform the motor would not in practice operate for more than an instant at exactly synchronous speed, and that, therefore, the unbalanced currents in the three phases would be of no importance. If, however, the angles ψ_1, ψ_2 and ψ_3 are not exactly equal, the total torque of the motor varies according to the relative position of the brushes and the magnetic field. This is very likely to be the case in practice, since on normal loads at synchronous speed the angles ψ_1, ψ_2 and ψ_3 are very small, and slight errors in setting the brushes become of considerable importance.* The setting here referred to is the manufacturer's setting, and is not within the control of the operator, as the amount of brush separation is.

From equation (1) if it is assumed that $r_1 = r_2 = r_3 = r$, $\beta_1 = \beta_2 + (2\pi/3)$, and $\beta_3 = \beta_1 + (4\pi/3)$, the total torque is proportional to

$$\{(\psi_1+\psi_2+\psi_3)+\tfrac{1}{2}(\eta_2+\eta_3)\ \cos\ 2\beta_1+\tfrac{1}{2}\sqrt{3}(\eta_3-\eta_2)\ \sin\ 2\beta_1\}$$

The first term in this expression is independent of the position of the magnetic field, the second and third are dependent on it, and it follows that for a given brush-setting the motor can operate against a varying torque (within limits) by a movement of the field, without departing permanently from synchronous speed. In effect this constitutes a locking action and the motor may operate for considerable periods at exactly synchronous speed, with resultant unequal heating of the phase windings and greater total heating. In the motor tested it was found that the variation in external torque possible without bringing the motor out of synchronism, for a constant brush-setting, was about 30 per cent of full-load torque. The values of η_2 and η_3, determined by measurement, were $\eta_2 = 2$ electrical degrees and $\eta_3 = 2\frac{1}{2}$ electrical degrees. The currents in the three phases were widely different while running at synchronous speed. In one case they were 106 amperes, 61 amperes, and 0 amperes respectively.

A similar investigation has been carried out to find the effect of inequality in the angles between centre lines of pairs of half brushes, and it was found that although this also caused a similar locking action at synchronous speed, the effect was not nearly so large (for the same error in degrees) as inequalities in the angles between half brushes.

It may also easily be seen that these errors will cause a periodic torque variation at speeds close to synchronism, which will result in corresponding speed oscillations. Thus operation close to synchronous speed will be unsatisfactory owing to speed oscillations, and operation at exactly synchonous speed will be unsatisfactory owing to the unbalanced currents. The importance of very careful setting of the brushes, therefore, need hardly be emphasized. As these out-of-balance currents are not reflected into the primary, the ordinary user would not suspect their presence until the motor gave trouble due to overheating.

* In the motor tested, these angles were found to differ by about 2 electrical degrees (two-thirds of a geometrical degree).

A CRITICAL RÉSUMÉ OF RECENT WORK ON DIELECTRICS.*

[REPORT (REF. L/T14) PREPARED BY MR. L. HARTSHORN, B.SC., AT THE NATIONAL PHYSICAL LABORATORY, AND RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.†]

PREFACE.

During recent years, electrical engineers throughout the world have come to realize that progress in the industry is largely retarded by the limitations and uncertainties of the insulating materials at its disposal.

Accordingly, although the Association is not yet in possession of adequate funds for a general attack upon the problem, it has decided to do all it can with available funds to prepare the ground. As a first step; the work of preparing a critical résumé of modern work on dielectrics was put into the hands of the National Physical Laboratory.

The object is to give a critical review of modern work and theories upon the subject of dielectric phenomena, extending over the past ten years.

This résumé is now being published for the advancement of the industry.

CONTENTS.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† The symbols adopted by the International Electrotechnical Commission have been substituted for those used in the original copy of the Report.

CONTENTS—*continued.*

I. DIELECTRICS IN GENERAL—POWER LOSS.

(*a*) *The ideal dielectric—Electric polarization or displacement.*

In the early days of electrical science all substances were divided into two classes—*Conductors* and *Insulators*. The characteristic property of a conductor is that "when a charge of electricity is communicated to any part of that substance, the electricity is rapidly transferred from places of high to places of low potential till the potential of the whole becomes the same" (Maxwell).*

The transference is not equally rapid for all substances, but is slower the greater the resistance of the substance or the smaller its conductance. Substances in which such a transference of electricity does not take place were called insulators. All bodies whose insulating power is such that when they are placed between two conductors at different potentials the electromotive force acting on them does not immediately distribute their electricity so as to reduce the potential to a constant value, were called by Faraday *Dielectrics*. Consider now a slab of dielectric bounded by two conducting planes A and B. The arrangement forms a condenser. If now one of the plates A or B be earth connected and the other be given a charge Q, then its potential will be raised to V, where

$$V = \frac{Q}{C}$$

C being a constant called the capacity of the condenser. The + charge Q on A induces an equal negative charge on B, and the two plates exert a force of attraction on each other. These actions of one plate on the other are considered to be exerted by means of the medium between them, i.e. the dielectric which is considered to be in a state of stress called *electric polarization*, the term polarization † signifying that any elementary portion of the dielectric has acquired equal and opposite properties on two opposite sides. In order to form a mental picture of the polarization of the dielectric we often imagine it crossed by lines of force, or lines of induction starting from the positive charge on A and ending on the negative charge on B.

Faraday discovered that the capacity of a condenser depends not only on the size and distance apart of the plates, but also on the nature of the dielectric medium. He defined the ratio of the capacity of a condenser with any given dielectric medium to the capacity of a condenser of the same size and form with air as dielectric as the *specific inductive capacity* of the dielectric.

Consider again the slab of dielectric bounded by the two conducting plates A and B. Let the plates, originally earth connected, be connected to a source of e.m.f. such as to maintain a difference of potential V between the plates. Immediately on connecting up, the condenser becomes charged with a quantity of electricity $Q = VC$, i.e., a charge $+Q$ flows * from the source of e.m.f. into A, an equal and opposite charge flows into B, and the dielectric becomes polarized. The charge Q flowing into the condenser is given by

$$Q = \epsilon C_a V$$

where V = potential difference between the plates,
ϵ = specific inductive capacity of the dielectric,
C_a = capacity of the plate condenser AB with air as dielectric.

If the dielectric is a "perfect" one, then when the charge Q has flowed into the condenser, equilibrium is reached and no further transfer of electricity takes place. There is now a potential gradient in the dielectric. It is subjected to the action of an electromotive force V acting from A to B and it is in a state of polarization. Maxwell conceived this polarization to consist in what he called an *electric displacement* produced by the electromotive force. He considered that although electricity cannot flow through a dielectric it can be displaced a certain amount within it, the displacement being in the same direction as, and proportional to, the e.m.f. producing it. The displacement is measured by the quantity of electricity crossing the unit of area, and this is a measure of the electric polarization. Thus electromotive force is considered to produce electric displacement just as mechanical force produces the displacement of an elastic body. Pursuing the analogy Maxwell called the ratio

$$\frac{\text{e.m.f.}}{\text{displacement produced}} = \text{coefficient of electric elasticity.}$$

* CLERK MAXWELL: "Electricity and Magnetism," vol. i, p. 48.

† In the text, polarization is used in the purely qualitative sense defined here. It is also sometimes used quantitatively as follows: The ether is supposed to permeate all matter, and thus the total displacement in the dielectric medium of any material condenser due to the application of an electric force F may be regarded as consisting of the part

$$\frac{1}{4\pi} \cdot \frac{F}{v^2}$$

in the ether, together with the part

$$\frac{\epsilon - 1}{4\pi} \cdot \frac{F}{v^2}$$

in the material, all the quantities being expressed in electromagnetic units. This part in the material is called the polarization of the material. Thus

$$\text{Polarization} = P = \frac{\epsilon - 1}{4\pi} \cdot \frac{F}{v^2} = a\frac{F}{v^2} \text{ (say)}$$

where $\epsilon = 1 + 4\pi a$.

a may be called the dielectric susceptibility. It is found that P may be interpreted as the electric moment per unit volume of the material. It is thus exactly analogous to the Intensity of Magnetization.

* It is probably more accurate to speak only of the motion of negative electricity, since in conductors and perfect dielectrics the electron is probably the only carrier of electricity. The argument, however, is in no way affected by such a change.

This coefficient varies inversely as the specific inductive capacity.

In the case considered, the total electric displacement across any cross-section of the dielectric between A and B is Q. Thus in charging the condenser, at the same time as the quantity of electricity Q flows from the source of e.m.f. along the connecting wire to A, a quantity of electricity Q crosses every cross-section of the dielectric from A towards B and a quantity Q flows out of B leaving it with a charge $-Q$. Thus the flow of electricity can be regarded as continuous round the whole circuit.

When the electromotive force is removed, the displacement disappears. Thus, suppose the condenser is discharged by joining the plates A and B by a wire. The quantity of electricity Q flows from A along the wire to B, whilst the polarization of the dielectric disappears. The displacement has subsided, a quantity of electricity Q crossing each cross-section of the dielectric from B towards A. Thus we have motion of electricity in the opposite direction to that in charging round the whole circuit.

Thus, says Maxwell,* whatever electricity may be, and whatever we may understand by the movement of electricity, the phenomenon which we have called electric displacement is a movement of electricity in the same sense as the transference of a definite quantity of electricity through a wire is a movement of electricity, the only difference being that in the dielectric there is a force which we have called electric elasticity which acts against the electric displacement and forces the electricity back when the electromotive force is removed; whereas in the conducting wire the electric elasticity is continually giving way, so that a current of true conduction is set up, and the resistance depends not on the total quantity of electricity displaced from its position of equilibrium, but on the quantity which crosses a section of the conductor in a given time.

Our ideas of the nature of electricity and its movement have crystallized out very considerably since Maxwell's time. A conductor is now regarded as a substance containing free electrons, i.e. electrons capable of moving about freely in the interstices between the atoms. When an electromotive force is applied to such a body there is a general drift of the electrons in the direction of the e.m.f. (or rather in the opposite direction since the electron is a negative charge) and this drift constitutes the conduction current. When the e.m.f. is removed the conduction current merely ceases.

A perfect dielectric is regarded as containing no free electrons. All its electrons are bound by forces of attraction to the positive nuclei of the atoms. Thus when an e.m.f. is applied to a dielectric there can be no general drift of the electrons, i.e. no conduction current. The electrons are, however, displaced somewhat from their equilibrium position against the action of the force of attraction binding them to their positive nuclei. The amount of the displacement is proportional to the force, and when the e.m.f. is removed the electrons immediately return to their equilibrium position under the action of the restoring force.

* Clerk Maxwell: "Electricity and Magnetism," vol. i, p. 64.

(b) *Conduction in dielectrics.*

It was very early realized that no substance could be regarded as a perfect insulator or dielectric, i.e. whenever an e.m.f. is applied to any actual dielectric, in addition to the sudden movement of electricity constituting the electric displacement or polarization of the dielectric, there was also a very feeble conduction current. Thus in order to specify the behaviour of any dielectric under the action of an e.m.f. we must have a knowledge of two constants:—

(i) A constant determining the electric displacement. The specific inductive capacity or dielectric constant ϵ serves this purpose.

(ii) A constant determining the conduction current—the specific conductivity σ, or the specific resistance ρ.

Suppose we have a slab of dielectric of area A and thickness l. Let an e.m.f. E be applied to its opposite faces. Then at the instant of applying the e.m.f. we shall have an electric displacement D given by

$$D = \frac{\epsilon}{4\pi v^2} F \text{ (in electromagnetic C.G.S. units)}$$

where F = electric intensity $= \dfrac{E}{l}$

v = velocity of light.

The total movement of electricity is thus

$$Q = D \times A = \epsilon \frac{A}{4\pi l} \times \frac{1}{v^2} \times E$$

In addition to this sudden displacement of electricity there will be a conduction current of amount

$$i_0 = \frac{A\sigma E}{l} = A\sigma F$$

which will persist as long as the e.m.f. is applied. If now the e.m.f. is reduced to zero, the electric displacement vanishes, i.e. there is a sudden rush of charge in the opposite direction and the conduction current ceases.

We regard the conduction current in such cases as due to the fact that the dielectric must contain a comparatively small number of free electrons in addition to the bound electrons pertaining to the electric displacement. Similarly it seems reasonable to suppose that a conductor contains a certain number of bound electrons in addition to its free electrons, and thus we may expect conductors to show dielectric properties to a certain extent, though these may be difficult to detect. In fact, it is not possible to draw a hard and fast line between conductors and dielectrics.

(c) *Dielectrics in practice.*

In practice dielectrics are used almost exclusively on account of their property of withstanding electric stress; they may be subjected to the action of large voltage gradients without allowing the passage of electricity through them. There is, of course, the small conductor current already referred to. This is usually termed the leakage current and is kept as small as possible. In

the perfect dielectric the only effect of the voltage gradient is to produce an electric displacement in the dielectric, which disappears when the voltage gradient is removed. A certain amount of energy is expended on the dielectric in producing the displacement and the dielectric gives up the same amount of energy when the electric field is removed. Thus when the perfect dielectric is placed in an alternating field, energy is alternately stored up and given back by the dielectric and there is no net loss of power.

All the dielectrics used in practice fall far short of the ideal of withstanding the voltage gradient with no net loss of power, and a great amount of research work has been done with the object of finding out the cause of the defects usually met with. In the following pages an attempt will be made to trace the course of these investigations up to their present stage. The defects of commercial dielectrics may be classed as follows:—

(i) *Leakage.*—The leakage current may become excessive, leading to a considerable loss of power.

(ii) *Breakdown.*—The electric elasticity of the dielectric gives way completely if it is subjected to a voltage gradient greater than a certain critical value.*

(iii) *Power loss in alternating fields.*—When used in alternating fields many dielectrics dissipate a considerable amount of power which causes a rise in temperature of the dielectric. This power loss is much greater than can be accounted for by the leakage current. It will be considered in detail later.

(*d*) *Quantities measured.*

In order to know how any dielectric will behave in practice we usually determine certain constants of the material.

Consider first the constants necessary to determine the leakage current. The current passing through the body of the dielectric is determined by the *volume resistivity* of the material, which is defined as the resistance between two opposite faces of a centimetre cube. In the case of solid dielectrics, however, the leakage current is found to consist of two parts, one flowing through the body of the material and the other flowing over the surface through a very thin film of moisture or other conducting material. This surface leakage current is determined by the *surface resistivity*,† which may be defined as the resistance between two opposite edges of a surface film one centimetre square. It is often convenient to express the total resistance between two conductors separated by a solid dielectric. This is called the *leakage resistance* ‡ or the *insulation resistance*. It is a function of both the volume and surface resistivities and the relative importance of the two varies enormously in different cases. The reciprocal of the leakage resistance gives the *leakage conductance*.

The power of the material to resist breakdown is usually specified by means of its *dielectric strength*, which is the voltage gradient just sufficient to cause breakdown.

* It must not, however, be imagined that the electrical breakdown of an insulator is in all cases strictly analogous to the mechanical breakdown of an elastic solid [see page 118 (g)].

† CURTIS: *Bulletin Bureau of Standards*, 1915, vol. 11, p. 378.

‡ *Ibid.*, p. 379.

The power dissipated in the dielectric when it is subjected to the action of an alternating field may be specified in a number of ways. Any system of conductors and dielectrics may be regarded as a condenser, and in dealing with the problem of dielectric losses it is convenient to suppose that we are simply dealing with a condenser, though actually the insulating material in any piece of electrical equipment may constitute the "condenser."

A condenser in which the dielectric is a vacuum dissipates no power when subjected to alternating voltage. It is a "perfect" condenser. If voltage of sine wave-form

$$v = V_0 \sin \omega t$$

is applied to such a condenser, the current is given by

$$i = V_0 C_0 \omega \cos \omega t$$

where C_0 is the capacity of the condenser. Thus the current leads the voltage by 90°, which must be the case since no power is dissipated. Such a condenser can only be obtained in practice by using a gas as the dielectric. When any solid or liquid dielectric is used,

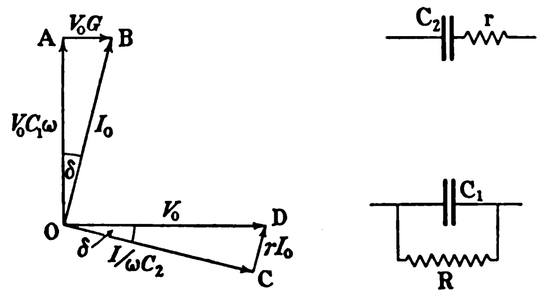

FIG. 1.—Power loss vector diagram illustrating effective series and shunt capacities.

a certain amount of power is always lost as heat in the dielectric. Thus the current no longer leads the voltage by exactly 90°, but by a slightly smaller angle (90° − δ), where δ may be called the "*loss angle*" of the condenser, or since δ is independent of the form of the condenser, the loss angle of the dielectric. If I and V are the effective current and voltage, the power loss is obviously given by

$$\text{Power loss} = W = IV \times \sin \delta,$$

i.e. Power factor = sin δ.

Such a condenser is usually regarded as being equivalent to a perfect condenser of capacity C_1 shunted by a very high resistance R $\left(\text{or conductance } G = \frac{1}{R}\right)$ the power loss being represented by that dissipated by the resistance. It may also be regarded as a perfect condenser of capacity C_2 in series with a small resistance r, which is the cause of the power loss.

Fig. 1 shows the vector diagram of an imperfect condenser and its equivalent circuits. In one case the current I_0 is regarded as consisting of two components, OA = $V_0C_1\omega$ being the current in the perfect condenser of capacity C_1 and therefore at right angles to the

applied voltage V_0, and AB $= V_0 G$ the component due to the shunt conductance G and thus in phase with V_0. Alternatively, the voltage V_0 is regarded as consisting of the two components OC:—

$$\mathrm{OC} = \frac{I_0}{\omega C_2}$$

due to the capacity C_2 and thus 90° out of phase with the current I_0, and CD the voltage drop in the series resistance r and thus in phase with the current I_0.

It is to be noted that the capacities C_1 and C_2 are not identical. We have

$$C_1 = \frac{I_0}{V_0\omega}\cos\delta \text{ — the equivalent shunt capacity.}$$

$$C_2 = \frac{I_0}{V_0\omega}\cdot\frac{1}{\cos\delta} \text{ — the equivalent series capacity.}$$

Also $$\tan\delta = \frac{G}{C_1\omega} = rC_2\omega.$$

Thus the two capacities are only the same when $\cos\delta$ is sensibly unity, i.e. when δ is very small. When this is the case we also have approximately

$$\text{Power factor} = \sin\delta = \delta = \tan\delta.$$

The wave-form of the current obtained when voltage of sine wave-form is applied to a dielectric has been directly determined in a number of cases by Thornton.* He found that in all cases the phase difference between current and voltage was somewhat less than 90°, as is indicated above, but that in certain cases the current wave was also distorted. In such a case it is no longer possible to find a combination of perfect condenser and resistance which represents exactly the behaviour of the condenser, though by ignoring the distortion we may represent it approximately in this manner. Fig. 2 shows the current and voltage wave-forms in two typical cases:—

1. In which there is no distortion, and
2. In which distortion occurs.

The quantity of electricity (Q) in the condenser at any instant may be found by integrating the current wave up to that instant, and thus a curve may be plotted showing the variation of Q during the cycle. If now Q is plotted against the corresponding values of V we obtain the figures shown at (c) and (d) corresponding to the two cases (a) and (b). The resemblance of these to magnetic hysteresis loops is obvious, and thus the power loss is sometimes regarded as due to "dielectric hysteresis." The power loss per cycle is, of course, determined by the area of the loop obtained. As will be shown later, the resemblance between the phenomena of power losses in dielectrics in alternating fields and hysteresis losses in iron in alternating magnetic fields is only superficial. The magnetic cycle depends very little on frequency, whereas the electric cycle depends entirely on frequency, i.e. at zero frequency there seems to be no loop but a straight line only. On this account many writers † deprecate the use of the term hysteresis in connection with the phenomena of power losses in dielectrics. Sometimes the loops are referred to as "cycles of viscosity," * but in the present state of our knowledge it is probably best not to use any term which assumes that the loss arises from any particular source.

The meaning of the term "capacity" as applied to a condenser in which there are power losses requires some attention. In the case in which there is no distortion in the current wave we have

$$v = V_0 \sin\omega t$$
$$i = I_0 \cos(\omega t - \delta)$$
$$Q = \frac{I_0}{\omega}\sin(\omega t - \delta) = Q_0 \sin(\omega t - \delta).$$

In this case the QV loop is an ellipse. Capacity is usually defined as the ratio Q/V, and for a perfect condenser the ratio is constant. Fig. 2 shows, however, that in the case considered, the ratio takes all values

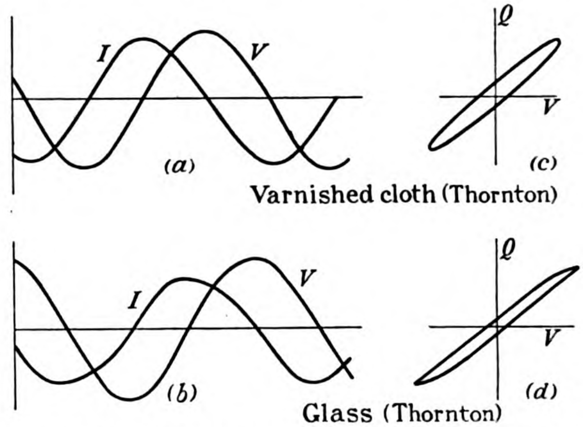

FIG. 2.—Distorted and undistorted waves with corresponding QV loops.

from $-\infty$ to $+\infty$ during a cycle. In such a case two definitions † of capacity have been used :—

1. The ratio $\frac{Q}{V}$ at the instant when Q has its maximum value. This is equal to

$$\frac{Q_0}{V_0\cos\delta} = \frac{I_0}{V_0\omega}\cdot\frac{1}{\cos\delta}$$

i.e. the equivalent series capacity.

2. The ratio $\frac{Q}{V}$ at the instant when V has its maximum value. This is equal to

$$\frac{Q_0\cos\delta}{V_0} \quad\text{or}\quad \frac{I_0}{V_0\omega}\cos\delta$$

i.e. the equivalent shunt capacity.

If β represents the angle between the axis of the ellipse and the V axis, then

$$\tan 2\beta = \tan 2\alpha\cos\delta$$

where $\alpha = \arc\tan\frac{Q_0}{V_0}$.

* THORNTON: *Proc. Phys. Soc.*, 1912, vol. 24, p. 301.
† See for example SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 711.

* J. GRANIER: *Bulletin de la Société Française des Électriciens*, 1923 vol. 3, p. 355, or J. GRANIER: *Rev. Gén. de l'Électricité*, 1921, vol. 10, p. 219.
† H. JORDAN: *E.T.Z.*, 1911, p. 127.

Thus as the loss angle increases, the axis of the ellipse approaches the V axis.

If we had a dielectric which possessed a certain small conductivity but was otherwise perfect, it would possess a QV loop as shown above. In this case it is obvious that the equivalent shunt capacity, i.e. definition (2), would give the true value, and thus we shall in all cases use this value when obtaining the effective capacity of a condenser at any particular frequency. The value may vary considerably with frequency, and as each value determines a value of the "dielectric constant" of the material, it becomes doubtful whether we are entitled to speak of the material as possessing a "dielectric constant." On this account the value of ϵ calculated from the effective capacity of a condenser under alternating voltage is often called the *permittivity* of the dielectric under the conditions of the test.

Summarizing, when dealing with any dielectric system subjected to alternating voltages, it is of importance to know

1. The effective capacity C.
2. The loss angle δ.

The power loss is given by

$$W = IV \sin \delta$$

where I and V are effective values ; or, since

$$C = \frac{I}{V\omega} \times \cos \delta$$

$$W = V^2 \times \omega \times C \times \tan \delta.$$

The loss angle δ is independent of the size of the condenser and depends only on the nature of the dielectric, but the loss W and capacity depend on the size and shape of the system, and to compare different materials we must consider the permittivity ϵ given by

$$\epsilon = \frac{C}{C_0}$$

C_0 being the capacity of a condenser of the same size and shape as C, but with air as dielectric. We then have

$$W = V^2 \times \omega \times \epsilon \times \tan \delta \times C_0$$

Thus the power loss in any material is proportional to the product of ϵ and $\tan \delta$.

Suppose we are dealing with a parallel-plate condenser of area A and thickness d.

Then

$$C_0 = \frac{A}{4\pi d} \times \frac{1}{v^2} \text{ absolute electromagnetic units}$$

$$= \frac{A}{3 \cdot 6\pi d} \times 10^{-12} \text{ farads}$$

$$\therefore W = \frac{10^{-12}}{3 \cdot 6\pi} \times \omega\epsilon \tan \delta \times \frac{A}{d} V^2 \text{ watts.}$$

If now we regard the energy dissipation as occurring uniformly throughout the dielectric we may write

$$\text{Power loss per cm}^3 = \frac{10^{-12}}{3 \cdot 6\pi} \omega\epsilon \times \tan \delta \left\{\frac{V}{d}\right\}^2.$$

The voltage gradient is V/d volts per cm. If we put g = voltage gradient in kilovolts per mm, we obtain

$$\text{Power loss per cm}^3 = 55 \cdot 5\epsilon \times \tan \delta \times f \times g^2 \times 10^{-6} \text{ watts}$$

where f = frequency.

Many workers* have expressed their results in an equation of this form. Others have expressed the power loss by means of the equivalent conductance G given by

$$W = V^2 G$$

$$= V^2 \frac{A\sigma}{d} = \left\{\frac{V}{d}\right\}^2 \sigma A d$$

σ is then called the "alternating-current conductivity" † of the dielectric. In this case we see that

Power loss per cm^3 = σ × (voltage gradient in volts/cm)^2.

$$\text{Also } \sigma = \frac{10^{-12}}{3 \cdot 6\pi} \times \omega\epsilon \times \tan \delta = \frac{10^{-12}}{1 \cdot 8} f \times \epsilon \times \tan \delta$$

Obviously σ may be regarded as the "specific power loss" of the material in question.

II. Dielectric after-effect—Absorption.

(a) *The anomalous properties of dielectrics.*

On the "ordinary" electromagnetic theory a dielectric is characterized by two quantities, the dielectric constant ϵ and the conductivity. In actual practice, the behaviour of dielectrics is found to be not solely determined by these quantities. All solid and liquid dielectrics show certain properties which seem to be quite independent of ϵ and σ, and these are usually referred to as their anomalous or abnormal properties. The power loss occurring in alternating fields is in practice the most important of these anomalies. The phenomena of "residual charge" and "absorption" are also of great importance. There is an intimate connection between these phenomena and the power loss with alternating current, and as "absorption" may be regarded as the more fundamental phenomenon, it will now be considered in some detail.

(b) *The polarization of dielectrics in constant fields.*

Consider the usual parallel-plate condenser with a perfect dielectric. Suppose initially the plates are connected together and to earth, and then at a given instant they are connected to a source of constant e.m.f. E. Current flows along the connecting wires into the condenser until it becomes charged with the quantity of electricity CE, where C is the capacity of the condenser. The current charging the condenser in this manner is termed the *normal charging current*. Its magnitude and duration depend on the resistance and inductance of the connecting wires and on the capacity of the condenser, being determined by the usual equation

$$L\frac{d^2 i}{dt^2} + R\frac{di}{dt} + \frac{i}{C} = 0$$

* Cf. F. W. Peek: *Gen. Elec. Rev.*, 1915, vol. 18, p. 1050. Also Minton: *Trans. A.I.E.E.*, 1915, vol. 34 (2), p. 1627.

† Cf. Fleming and Dyke: *Journal I.E.E.*, 1912, vol. 49, p. 323.

In practice R and L are usually very small, and the current has fallen to zero in a very small fraction of a second.

If the condenser possesses an appreciable conductance, then superposed upon this normal charging current there will be a constant leakage current. After the normal charging current has fallen to zero, this conduction current will continue to flow, so long as the e.m.f. is maintained. This will be referred to as the *normal conduction current*.

If now the e.m.f. be suddenly reduced to zero, the condenser discharges through the connecting wires giving the *normal discharge current* which extremely rapidly falls to zero, as did the normal charging current. The normal conduction current merely ceases the instant the e.m.f. is reduced to zero.

When the above experiment is made with any ordinary solid or liquid dielectric, the charging current is found to contain another component in addition to the normal charging and conduction currents. After the normal charging current has ceased (the time required for this can be calculated), a current, more or less rapidly decreasing with time, is observed to be flowing into the condenser. This current may continue to decrease for hours; cases have been observed in which the decrease has persisted for months.* Eventually either the current becomes too small to be detected or else a constant value is reached. This constant current is, of course, the normal conduction current. Thus the total current in charging consists of

1. The normal charging current $i_1(t)$.
2. The normal conduction current = constant = a.
3. *The anomalous charging current* or *absorption current* $i_2(t)$.

So that $$I = i_1(t) + a + i_2(t)$$

The charging current having continued until the steady state is reached, suppose now the e.m.f. is reduced to zero—the condenser is short-circuited. There is first the sudden rush of current in the opposite direction to the charging current, constituting the normal discharge current. In many cases after this has died down there is also observed an *anomalous discharging current* similar to the anomalous charging current but in the opposite direction. This also may persist for months. The condenser being short-circuited, there is no potential difference between its terminals, and thus no normal conduction current, during discharge. Thus the total current during discharge is given by

$$I' = i'_1(t) + i'_2(t).$$

The normal charge of the condenser is, of course, reversible so that, the circuit constants being the same in charge and discharge, we have

$$i'_1(t) = - i_1(t)$$

time being measured from the instant at which the charge and discharge respectively begin. In the case of most solid dielectrics we also find that

$$i'_2(t) = - i_2(t)$$

* SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 759.

i.e. the abnormal charging current may also be regarded as being quasi-reversible. In such cases, the charge conveyed by the abnormal current is sometimes regarded as being "absorbed" by the dielectric during charge and liberated again during discharge. The term, though often convenient, can only be regarded as a very loose one. Many writers do, however, refer to these phenomena as *absorption phenomena*.

In other cases (generally with liquid dielectrics), although we find an anomalous charging current as described above, no anomalous discharge current is observed, or at any rate the anomalous discharge current is very small compared with the anomalous charging current.* It seems quite possible that we are dealing with quite different phenomena in the two cases, though the behaviour in charging is very similar. The normal charging current in the connecting wire corresponds to the production of a certain electric displacement in the dielectric, and the normal discharge current is merely the collapse of this displacement, the process being reversible. By analogy, when the anomalous current is quasi-reversible we may regard it as corresponding to an *anomalous displacement* in the dielectric. The normal conduction current is, of course, not reversible. Thus when the anomalous current is not reversible we may regard it as an *anomalous conduction* current. Thus for convenience we may assume there are two kinds of anomalies :—

1. Anomalous displacement.
2. Anomalous conduction.

It must not be taken that these terms imply any knowledge of the mechanism of the actions concerned.

The production of electric displacement by electric force has been compared with the production of deformation in an elastic body by mechanical force. Similarly anomalous electric displacement is analogous to elastic after-effect and the phenomena of fatigue in elastic bodies. On this account it is often termed dielectric after-effect.

(*c*) *The residual charge.*

The phenomena of anomalous displacement become much less simple when the condenser plates are not maintained at constant voltage, yet much work has been done under such conditions, i.e. having charged the condenser for a definite time, instead of discharging by joining the plates by a wire and so maintaining zero potential difference between them after the normal discharge is allowed to pass, one terminal of the condenser is left insulated. Under these conditions a charge of the same sign as before is observed gradually to build up on the condenser plates. This, of course, corresponds to the charge conveyed by the anomalous discharging current in the previous case. It rises to a maximum value and then slowly disappears (due no doubt to leakage). This is known as the *residual charge*.† It is obviously the same phenomenon that we have called anomalous displacement, but under

* SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 753. Also TANK: *Ann. der Physik*, 1915, vol. 48, p. 349.
† CLERK MAXWELL: "Electricity and Magnetism," vol. 1, p. 380.

more complicated conditions. In the main we shall confine ourselves to the simple conditions.

(*d*) *Variation of capacity with time of charge and discharge.*

This again is seen to be another aspect of the phenomenon of anomalous displacement, though normal and abnormal conduction may play a part. The effect is observed when the capacity of a condenser is measured by means of a ballistic galvanometer or fluxmeter. The throw of the instrument is observed when the circuit is made or when the condenser is allowed to discharge through it. It is obvious that the quantity of electricity measured will include varying amounts carried by the anomalous current, depending on the time of swing of the instrument, the time during which the e.m.f. was applied, the time during which the condenser is left insulated and charged, the leakage resistance, and the law of decay of the anomalous current. In considering the results of such tests, it is obvious that the conditions must be known if the results are to be of any value.

The variation of capacity with frequency when the condenser is subjected to alternating voltage is also another aspect of the same phenomenon. It will be considered in detail later.

(*e*) *Methods of measurement.*

In the present section we shall confine ourselves to experiments in which the behaviour of the dielectric is

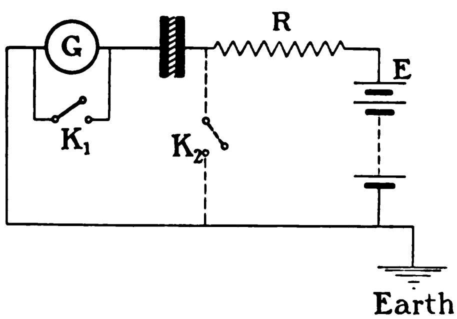

FIG. 3.—Measurement of anomalous current with series galvanometer.

studied whilst under the action of a constant electric force. The various methods used may be divided into two classes:

Those in which the current flowing into the condenser is measured as a function of time.

Those in which the total charge on the condenser or the total electric displacement or polarization is measured as a function of time.

(i) *Experiments in which the current is measured.*

In the methods of the first class we merely have to measure the current produced by a given voltage at various instants after the application of the voltage. The value of the current will depend enormously on the size of the condenser and the nature of the dielectric, but usually it becomes quite small in a very short time so that a sensitive galvanometer, or a still more sensitive instrument, is required.

1. The simplest possible case is shown in Fig. 3. This is the usual arrangement of galvanometer and battery used for insulation resistance measurements. The key K_1 short-circuits the galvanometer while the normal charging current passes. The galvanometer is used with various shunts so that a great range of current values can be measured. This arrangement is sufficient to measure the current until it decreases to something of the order 10^{-9} amperes.* What we measure in this case (assuming the galvanometer is short-circuited until the normal charging current has ceased) is $a + i_2(t)$. The variation of this with time is observed until it becomes constant. This constant value is a, and by subtracting it from each of the previous values we get $i_2(t)$. The discharge current is measured by closing the key K_2 (keeping K_1 closed until the normal discharge has ceased and then opening it). In this case there is no leakage current a and what we measure is simply $i_2'(t)$.

(The high resistance R protects the galvanometer against accidental short-circuits in charging, and also protects the battery when K_2 is closed. Its resistance is always small compared with the effective resistance of the dielectric.)

Measurements have been made in this way by many observers, including Schweidler,† on petroleum, toluol,

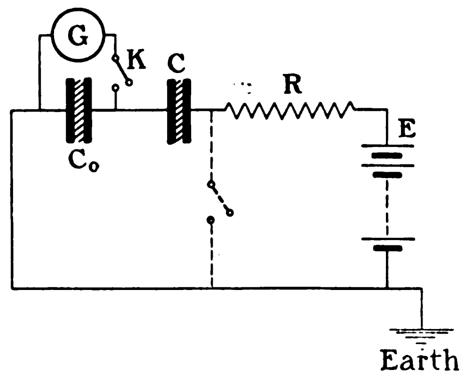

FIG. 4.—Measurement of anomalous current with ballistic galvanometer and condenser.

glass, mica and paraffined paper; Curtis,‡ on a very good range of solid dielectrics, examined chiefly volume resistivity and surface leakage; Wagner § on gutta percha, balata, rubber, ebonite, paraffin, fibrous materials, etc.; Lübben || on a large selection of the papers used in telephone cables.

2. For measuring the current when it has become smaller than 10^{-9} amps. the arrangement shown in Fig. 4 is sometimes convenient. The current through the dielectric C which is too small for the galvanometer G to detect is allowed to flow for a certain time Δt into the condenser C_0 (which is large compared with C).

* CURTIS: *Bulletin Bureau of Standards*, 1914, vol. 11, p. 363.
† SCHWEIDLER: *Ann. der Physik*, 1907, vol. 34, p. 711.
‡ CURTIS, *loc. cit.*
§ K. W. WAGNER: *Archiv. für Elektr.*, 1914, vol. 3, p. 67.
|| LÜBBEN: *Archiv. für Elektr.*, 1921, vol. 10, p. 283.

The key K is then closed and the charge ΔQ which has collected on C_0 is measured by the throw of the galvanometer. The mean current in the interval Δt is then given by

$$\frac{\Delta Q}{\Delta t}.$$

The circuit must be so arranged that the potential difference across C_0 is always small compared with the e.m.f. of the battery E. With this arrangement currents of 10^{-9} to 10^{-13} amps. are conveniently measured. It has been used by Curtis* and Schweidler.†

3. If still smaller currents have to be measured an electrometer may be used with advantage. The arrangement is shown in Fig. 5. The small current through C is allowed to charge up the electrometer for a time interval Δt. Let e be the potential reading indicated by the electrometer after this time. Let C_1 be the capacity of the electrometer and C_0 that of the shunting condenser. Then the charge which has flowed into the

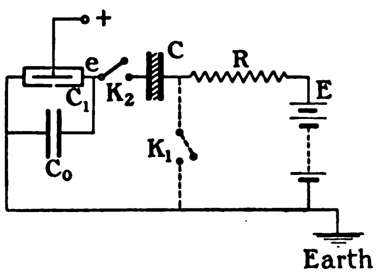

FIG. 5.—Measurement of anomalous current with electrometer.

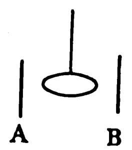

FIG. 6.—Thornton's polarization experiment.

electrometer and condenser is $(C_1 + C_0)e$ and then the mean current during the time Δt is

$$i = \frac{(C_1 + C_0)e}{\Delta t}.$$

As in the previous case, e must be kept small compared with E. Obviously the discharge current can also be measured with this arrangement. C_0 is chosen to give the most convenient sensitivity. Currents of 10^{-13} and 10^{-15} amps.* may be measured in this way. The method has been used by Curtis,‡ S. W. Richardson § (who made experiments on iceland spar, quartz and rock salt), and Tank.‖

4. In some cases it is desired to measure the charging current a small fraction of a second after applying the electromotive force. This cannot be done with the above circuits unless special arrangements are made for operating the switches. Arrangements for making such measurements have been described by Schweidler,¶ Jordan,** and Tank.‖ Jordan used a rotating commutator arrangement whereby the variations of the abnormal charging current in the first 2 seconds after applying the voltage could be explored. Tank used the circuit shown in Fig. 3 with a Helmholtz pendulum for opening the contacts K_1 and K_2 with time intervals of 0·0023 to 0·22 second. The electrometer then measures the total charge which has flowed in this small interval. One advantage of working with very small time intervals is that the abnormal charging current is then comparatively large, so that the leakage current is negligibly small compared with it. In all cases, of course, the effect of the leakage current must be taken into consideration.

(ii) *Experiments in which total charge or polarization is measured.*

1. A most ingenious method for making such measurements has been described by Thornton.* A sample of the dielectric to be studied is made up into the form of an ellipsoid. This is suspended by a quartz fibre between two parallel plates A and B, Fig. 6, between which a constant voltage is maintained. Thus the ellipsoid is situated in an electrostatic field and becomes polarized. If now the ellipsoid be made to execute small oscillations about its position of rest, the time of swing of these oscillations is obviously a function of the extent to which the ellipsoid has become polarized. The experiment is analogous to the oscillations of a magnet in a magnetic field. Thornton investigated the phenomenon mathematically and from the time of swing of the ellipsoid at any instant was able to deduce the value of

$$\epsilon = \frac{\text{Polarization}}{\text{Electric force}}$$

at that instant. The variation of ϵ with time and with the value of the electric force was investigated. The whole arrangement was in a vacuum and was carefully dried by phosphorous pentoxide.

2. H. A. Wilson † has used the arrangement shown in Fig. 7, by which the capacity of the sample C_2 is compared with that of an air condenser C_1. He gives the formula

$$\frac{C_2}{C_1} = \frac{\left(1 + a\frac{e}{V}\right)}{\left(1 - a\frac{e}{V} + \epsilon t\right)}$$

where a is a constant of the circuit and e is the electrometer reading. ϵt is a term representing the effect of conduction in the sample, t representing time. The reading e is taken at various times. When t is very large

$$\frac{C_2}{C_1}$$

becomes constant and thus ϵ may be found. Then using this value, the variation of

$$\frac{C_2}{C_1}$$

i.e. of C_2, may be found for the previous values of t.

(*f*) *Experimental results.*

When the results of different investigators are examined it is found that their conclusions are often

* CURTIS: *Bulletin Bureau of Standards*, 1914, vol. 11, p. 363.
† SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 750.
‡ CURTIS: *Bulletin Bureau of Standards*, 1914, vol. 11, p. 364.
§ S. W. RICHARDSON: *Proc. Roy. Soc.*, 1916, vol. 29, p. 41.
‖ TANK: *Ann. der Physik*, 1915, vol. 48, p. 307.
¶ SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 751.
** JORDAN: *Verh. Deutsch. Phys. Ges.*, 1912, vol. 14, p. 451.

* THORNTON: *Proc. Phys. Soc.*, 1910, vol. 22, p. 186.
† H. A. WILSON: *Proc. Roy. Soc.*, 1909, vol. 82, p. 409.

widely different. It seems not improbable that there are several different phenomena which it is almost impossible to separate, e.g. the true anomalous displacement, i.e. a phenomenon occurring within the molecule, effects of inhomogeneity of structure, and effects due to the migration of ions as in electrolysis.

Consider first the phenomena usually met with in the case of solid dielectrics, i.e. the reversible anomalous charge.

(i) It seems to be generally agreed that in such cases there is an anomalous charging current, which is comparatively large immediately after the voltage is applied, but which rapidly decreases with time. This current is found to be proportional to the applied voltage and to vary inversely as the thickness of the sample (i.e. it is proportional to the voltage gradient), the variation

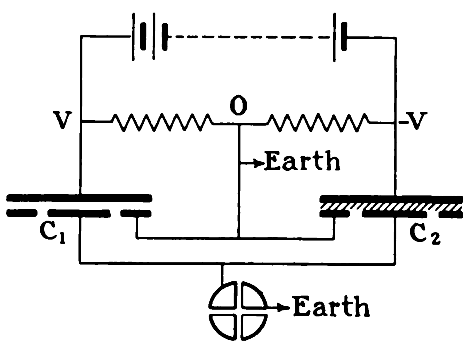

FIG. 7.—Wilson's circuit for measuring the variation of capacity with time.

with time being unaffected by change of voltage gradient.* Thus we may write :—

$$i_2(t) = \beta \times C_0 \times E \times \phi(t)$$

where β and the parameter of the characteristic time function $[\phi(t)]$ are constants of the material, and C_0 is the geometric capacity of the condenser.

(ii) Most observers also have found that after the dielectric has been charged until the anomalous current has become zero, and then discharged, the anomalous discharge current is given by

$$\begin{aligned} i_2'(t) &= -\, i_2(t) \\ &= -\,\beta \times C_0 \times E \times \phi(t). \end{aligned}$$

This was recently verified by Lübben † for telephone cable paper, but most observers in recent work have taken this for granted, and confined their attention either to charging current alone or the discharge current.

(iii) There seems to be some uncertainty as to the form of the time function $\phi(t)$. Many observers have found

$$\phi(t) = Bt^{-m}$$

where the constant $m < 1$. This law has been given by

* SCHWEIDLER : *Ann. der Physik*, 1907, vol. 24, p. 762.
† LÜBBEN : *Archiv. für Elektr.*, 1921, vol. 10, p. 291. Also SCHWEIDLER, *loc. cit.*

Hopkinson,* Schweidler,† Ashton,‡ Jordan,§ Lübben,‖ and others holding for various dielectrics, and there is no doubt that over a restricted time interval it is capable of representing the observed results in many cases. For values of t which are either very short or very long, it is doubtful whether it applies. Two difficulties stand in the way of its acceptance.

1. When $t = 0$, $\phi(t) = \infty$, which would mean an infinitely large initial current.

2. The total residual charge flowing into the condenser is given by

$$\int_0^\delta i_2(t)dt$$

where δ represents the time of charging, and

$$\int_0^\delta Bt^{-m}\,dt = \frac{B\delta^{1-m}}{1-m}$$

which is finite as long as δ is finite, but becomes infinite when $\delta = \infty$. This would mean that the residual charge increases indefinitely as long as the voltage is applied, whereas experiment shows that it reaches a finite limiting value.¶

In connection with (1) it is interesting to note that the experiments of Tank ** and Jordan,†† in which the current corresponding to very small values of t was measured, gave a law of the above form. It was anticipated that as t became smaller and smaller the current would approach a finite limiting value. Actually, although Tank was able to get down to $t = 0{\cdot}00033$, he was not able to obtain evidence of this. What actually happens as t gets smaller is that one gets into the region in which the normal charging current is large and thus the condenser is no longer under constant voltage. Over the range which could be investigated, no departure from the law was detected. The variation of capacity with time is obviously given by

$$C = C_0 + \int_0^t i_2(t)dt$$

and if $\quad i_2(t) = Bt^{-m}$

we have $\quad C = C_0 + \dfrac{B}{1-m}t^{1-m}$

H. A. Wilson ‡‡ gave as the result of his experiments the law

$$C = C_0[1 + B\log(1 + pt)]$$

This corresponds to an anomalous charging current of the form

$$i_2(t) = V\frac{dC}{dt} = \frac{VC_0Bp}{1+pt} = \frac{VC_0B}{t+1/p}$$

* J. HOPKINSON : *Phil. Trans.*, 1876, vol. 166, p. 489 ; *Phil. Mag.*, 1876, vol. 2, p. 314 ; *Phil. Trans.*, 1877, vol. 167, p. 599 ; *Proc. Roy. Soc.*, 1876, vol. 25, p. 496.
† SCHWEIDLER : *Ann. der Physik*, 1907, vol. 24, p. 752.
‡ A. W. ASHTON : *Phil. Mag.*, 1901, vol. 52, p. 501.
§ H. JORDAN : *Verh. Deutsch. Phys. Ges.*, 1912, vol. 14, p. 451.
‖ LÜEBEN : *Archiv. für Elektr.*, 1921, vol. 10, p. 291. Also SCHWEIDEER, *loc. cit.*
¶ See, for example, THORNTON : *Proc. Phys. Soc.*, 1910, vol. 22, p. 186.
** TANK : *Ann. der Physik*, 1915, vol. 48, p. 307.
†† H. JORDAN : *Verh. Deutsch. Phy. Ges.*, 1912, vol. 14, p. 451.
‡‡ H. A. WILSON : *Proc. Roy. Soc.* 1909, vol. 82, p. 409.

This may be written

$$i_2(t) = \frac{a}{t+b}$$

A formula of this form was also given by Trouton and Russ,* and Wilson pointed out that one set of observations of Schweidler's also obeyed this law. However, Schweidler's other observations do not correspond to it, and it does not seem to be capable of such wide application as the form $i_2(t) = Bt^{-m}$ although it gives a finite value for $i_2(t)$ when $t = 0$.

A most comprehensive and valuable set of measurements on commercial dielectrics has been made by K. W. Wagner.† He measured the anomalous discharge current after a charge of very long duration, using the simple galvanometer method [(*e.*)1]. He found that although the formula

$$i_2(t) = Bt^{-m}$$

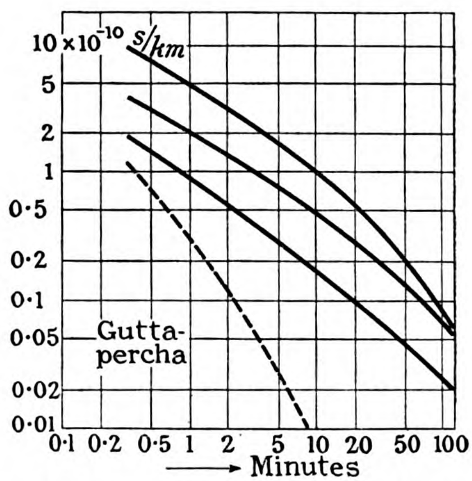

FIG 8.—Anomalous current as a function of time (gutta-percha).

could be applied in most cases over a limited time range, it did not fit all the results, expecially when the observations are extended over a long time. Typical curves are shown in Fig. 8. They are for gutta-percha (two samples) at various temperatures. For convenience $\log i_2(t)$ is plotted against $\log t$. The law $i_2(t) = Bt^{-m}$ would, of course, give a straight line of slope m

$$\log i_2 = -m \log t + \log B.$$

Actually, the line sooner or later becomes curved. These results of Wagner's illustrate the way in which the anomalous current is affected by temperature. The curves show (1) that the anomalous current, i.e. the "absorption," increases rapidly as the temperature rises; (2) that the variation with time is not so much affected by the change of temperature. These results are typical of dielectrics in general. Very similar results were given by Schweidler ‡ for glass. Schweidler stated that the law $i_2(t) = Bt^{-m}$ held approximately at all temperatures, but whereas B increased strongly with temperature, m was practically unaffected.

Wagner has given a formula which he considers more accurate than $i_2(t) = Bt^{-m}$, but as it is very complicated and arose out of theoretical considerations, discussion of it will be deferred until the theory is considered.

Various authors have given formulæ expressing the time variation of the discharge current with varying times of charge. In such cases we have introduced another variable and the formulæ become correspondingly more complicated. As no attempt has usually been made to connect these formulæ with other work, they will not be considered here.

Thornton * did not give any formula representing his results. He described the polarization produced by a constant field as consisting of three parts :—

1. A very rapid rise—the normal charge,
2. Then a slow charge at a uniform rate,
3. And finally an approach to saturation.

This does not seem to be consistent with the results of other observers. The point will be referred to later.

(iv) *Hopkinson's † Superposition Law.*

We have so far only considered the laws of the anomalous current under the condition of constant voltage. Consider now the case of a dielectric charged for a certain time τ with constant voltage and then discharged by short-circuiting. Suppose the anomalous charging current is given by

$$i_2(t) = f(t)$$

where t is reckoned from the instant at which the voltage was applied.

Then Hopkinson stated as the result of his experiments that the anomalous discharge current is given by

$$i_2'(t) = f(t) - f(t+\tau)$$

t now being reckoned from the instant at which the voltage is reduced to zero. Thus we may regard the current $i_2'(t)$ as consisting of two components, the first $f(t)$ being exactly similar in its time variation to the abnormal charging current but in the opposite direction, and the second $f(t+\tau)$ being merely a continuation of the abnormal charging current. It is as though the reduction of the voltage to zero, instead of annulling the effect of the initial application of the electrostatic field, merely superposes upon the current first produced, another one of the same time function but in the opposite direction. Thus the behaviour of any actual dielectric sample depends on the whole of its past history. (This brings out the importance of short-circuiting a sample for at least several hours before making any test on it, so as to allow the currents which have been started in it to die down.)

This is Hopkinson's Superposition Principle. Certain consequences of it are of particular interest.

* TROUTON and RUSS: *Phil. Mag.*, 1907, vol. 13, p. 578.
† K. W. WAGNER: *Archiv. für Elektr.*, 1914, vol. 3, p. 67.
‡ SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 759.

* W. M. THORNTON: *Proc. Phys. Soc.*, 1910, vol. 22, p. 186.
† HOPKINSON: Original papers, vol. 2.

1. After charging for an infinite time, the anomalous discharge current is given by

$$\begin{aligned} i_2'(t) &= f(t) - f(t + \infty), \\ &= f(t), \text{ since } f(\infty) \text{ is zero}, \\ &= i_2(t)\,; \end{aligned}$$

$i_2(t)$ and $i_2'(t)$ are of course in the opposite direction.

2. In the case in which we charge for time τ and then discharge, we find

$$\int_0^\infty i_2'(t)dt = -\int_0^\tau i_2(t)dt$$

i.e. the total charge conveyed out of the condenser by the abnormal discharge current is equal to the charge carried into the condenser by the abnormal charging current in the time of charging τ. Measurements made by Ashton * on a cable are not in agreement with this. Results obtained by Ashton seem to indicate that quantity carried out during discharge is twice that carried in by $i_2(t)$. Thornton † quotes this result and explains it by saying that the charge goes in under constant voltage and comes out under decreasing voltage, and the energy of charge and discharge being the same, the "quantity" of discharge is double that of "charge." The case is, however, not so simple as this. In discharge the condenser is short-circuited, and therefore the potential difference between its terminals is very nearly zero, and thus only a very small percentage of the energy which goes into the condenser during the abnormal charge comes out of it, if it is discharged by short-circuiting (since the abnormal discharge current is known to be of the same order as the abnormal charging current).

The Superposition Principle has been extended to cover cases in which the voltage varies in any manner.‡ Suppose the applied p.d. is changed by a series of increments Δ_0E, Δ_1E, Δ_2E . . . at the instant 0, t_1, t_2, t_3 . . . . Then the resultant abnormal charging current may be considered as a superposition of the charging currents due to each of the increments, these component charging currents all being considered independent of each other. Thus the resultant current is given by

$$i_2(t) = \beta C[\Delta_0E\,.\,f(t) + \Delta_1E.f(t - t_1) + \Delta_2E.f(t - t_2) + \ldots]$$

If now the applied p.d. varies according to the function $E(t)$, then

$$i_2(t) = \beta C\int_{-\infty}^{t}\frac{dE(u)}{du}\cdot f(t-u)du.$$

If this generalized Superposition Principle be true, then if we charge a dielectric until the steady state is reached and then discharge it, then whether we discharge by short-circuiting or by slowly lowering the voltage the total quantity carried out by the residual discharge current is equal to the quantity carried in during charge. Suppose now we charge a condenser until it has absorbed a certain quantity of electricity consisting of normal charge q_N and residual charge q_R. Then the work done in charging is

$$W = \tfrac{1}{2}q_NV + q_RV$$

where V is the applied voltage. Suppose now the condenser is discharged by lowering the voltage by an infinite number of infinitesimal steps, allowing the steady state to be reached after each step. Then when the discharge is completed, the Superposition Principle requires that the residual charge released is equal to q_R. But the potential during discharge has fallen uniformly so that the energy given back by the condenser in discharge is

$$W_1 = \tfrac{1}{2}V(q_N + q_R).$$

Thus the net loss of energy in this case is $\tfrac{1}{2}q_RV$, i.e. half the energy required to store up the abnormal charge. As we have seen when we discharge by short-circuiting, the whole of this energy is lost. Thus it is evident that if the "absorption" current obeys the Superposition Principle a certain amount of energy is lost whenever the condenser is charged, unless it is charged and discharged infinitely slowly. The amount of this loss evidently depends on the total amount of charge "absorbed" and the rate of the charge and discharge. It is also obvious that when the condenser is subject to alternating voltage there will be a certain loss of energy in every half cycle, and that this energy loss is quite independent of any leakage resistance. The laws followed by the power loss when the voltage is of sine wave-form will be subsequently developed, continuing the present line of argument. Meanwhile, it is to be noted that the result obtained by Ashton and quoted by Thornton is contrary to the Superposition Principle and that both cannot be accepted. Ashton in his paper was by no means confident about the interpretation of the experiments, and being an isolated case the result cannot be accepted without further inquiry.

(v) *The internal e.m.f. of polarization.*

This is a quantity introduced by Curie * and measured by S. W. Richardson.† It merely represents another way of regarding this same phenomenon of the residual discharge current. Suppose an e.m.f. E is applied to a specimen for a given time and is then reduced to E'. If E' is greater than a certain value P then the "absorption" current continues in the same direction, but if $E' < P$ the absorption current is in the opposite direction. Richardson has called the critical value P the internal e.m.f. of polarization under the condition prevailing. He measured it by trial, using a potentiometer arrangement for varying the voltage.

It is interesting to see what P means. Applying the Superposition Principle to the case considered, the equation

$$i = E\,.\,f(t) - (E - E')\,.\,f(t - \delta)$$

gives the current after the reduction of voltage to E' at time δ. (Normal charges are not considered here.) Thus P is defined by

$$0 = E\,.\,f(t) - (E - P)\,.\,f(t - \delta) \text{ when } t = \delta$$

$$P = E\left[1 - \frac{f(t)}{f(t-\delta)}\right] \text{ where } t = \delta$$

i.e. $$P = E\left[1 - \frac{f(\delta)}{f(0)}\right].$$

* A. W. Ashton: *Phil. Mag.*, 1901, vol. 52, p. 501.
† W. M. Thornton, *loc. cit.*
‡ Schweidler: *Ann. der Physik*, vol. 24, p. 717, 1907.

* Curie: *Annales de Chimie*, 1889.
† S. W. Richardson: *Proc. Roy. Soc.*, 1916, vol. 92, p. 101.

Richardson states that P increases with the time of charging, very rapidly at first and more slowly afterwards. This is borne out by the above formula. He also states that in order to determine the true resistance of the specimen this e.m.f. must be taken into account. He writes

Charging current $= \frac{dQ}{dt} + \frac{E-P}{R}$, where $\frac{dQ}{dt}$ is the rate at which charge is accumulating, E is the applied e.m.f., and R the true resistance. He has determined R for quartz and iceland spar, using the definition, and of course obtains higher values than would be obtained by neglecting P. There is, however, another side to this question. The actual conduction current is i_c, say. If E is the applied voltage, then, neglecting P, the resistance is

$$\frac{E}{i_c} = R$$

and the power expended is

$$Ei_c = \frac{E^2}{R}.$$

If now we take Richardson's definition

$$R_1 = \frac{E-P}{i_c}$$

we can no longer write

$$\text{Power expended} = \frac{E^2}{R_1}$$

since the power expended is certainly equal to the product of applied voltage and conduction current. Thus from the point of view of energy dissipation the ordinary definition of resistance is more convenient, although it may not necessarily mean that the resistivity and the movement of electricity within the dielectric is uniform throughout the sample and determined by

$$\frac{RA}{l}$$

where A = cross-section, l = length, and R is resistance. R must be taken as merely a measure of the total power expended by the conduction current.

(*g*) *Absorption in alternating fields.*

We have seen that when a dielectric is subject to alternating voltage it is to be expected that the anomalous charging current will cause an increase in the apparent capacity, the amount of such increase depending on the time taken to complete a cycle, i.e. the frequency. Further, if this anomalous current obeys the Superposition Principle, there must be a certain loss of power also, depending on the frequency and quite independent of the conductor current. The relation between these effects and the behaviour of the dielectric under constant voltage was worked out by Schweidler.* We shall follow his reasoning. We have obtained the general equation for the anomalous current

$$i_2(t) = \beta C \int_{-\infty}^{t} \frac{dE(u)}{du} \cdot f(t-u)du$$

where $E(u)$ expresses the variation of the applied voltage with time, and $\beta Cf(t)$ is the anomalous current produced by the application of unit e.m.f. at the time $t = 0$.

If now the voltage is of sine wave-form, we have

$$E(u) = E_0 \sin \omega u$$

$$\frac{d}{du}E(u) = \omega E_0 \cos \omega u$$

$$\therefore \quad i_2(t) = E_0 \omega \beta C \int_{-\infty}^{t} \cos \omega u \,.\, f(t-u)du$$

$$= E_0[M \cos \omega t + N \sin \omega t]$$

where
$$M = \omega\beta C \int_0^{\infty} f(x) \,.\, \cos \omega x \,.\, dx$$

$$N = \omega\beta C \int_0^{\infty} f(x) \,.\, \sin \omega x \,.\, dx$$

and
$$x = (t-u)$$

This determines the abnormal current. Superposed upon this are the normal charging current $\omega E_0 C \cos \omega t$ and the normal conduction current $GE_0 \sin \omega t$. Thus the total current is

$$i = E_0[(\omega C + M) \cos \omega t + (G + N) \sin \omega t].$$

Thus the effective capacity is given by

$$C_{effective} = C + \frac{M}{\omega}$$

$$= C + \beta C \int_0^{\infty} f(x) \,.\, \cos \omega x \,.\, dx$$

Thus if
$$\frac{\Delta C}{C}$$

represents the fractional increase of capacity due to "absorption"

$$\frac{\Delta C}{C} = \beta \int_0^{\infty} f(x) \,.\, \cos \omega x \,.\, dx$$

Also, the power loss is given by—

$$\text{Power loss} = \frac{E_0^2}{2}(N + G)$$

i.e. if E is the effective voltage, the power loss due to "absorption" is

$$W_1 = E^2 \beta C \omega \int_0^{\infty} f(x) \sin \omega x \,.\, dx$$

Thus if the function $f(x)$ is known, both the power loss and the change of capacity with frequency can be calculated. It is worth noting that the power loss should be proportional to the square of the voltage if the Superposition Principle is true.

We have seen that our knowledge of the function $f(x)$ is not altogether satisfactory. The formula most usually given is

$$f(t) = Bt^{-m}$$

where m is a constant less than unity.

This leads to the formulæ

$$\frac{\Delta C}{C} = \beta \omega^{m-1} \Gamma(1-m) \cos \frac{(1-m)\pi}{2} = B' \omega^{m-1}$$

* SCHWEIDLER, *loc. cit.*

and

$$W_1 = E^2\beta C\omega^m \frac{\pi}{2\Gamma(m)\cos\dfrac{(1-m)\pi}{2}} = E^2 A\omega^m$$

A and B are obviously constant for a definite value of m, and a definite size of specimen. This result is of great importance as showing how the power loss varies with frequency. The tests made at the N.P.L. on varnished cloth have supplied a striking verification of these equations over a limited range of frequency.

For power loss due to leakage and absorption,

$$\tan\delta = \frac{1}{C\omega} \cdot \frac{G + A\omega^m}{1 + B'\omega^{m-1}}.$$

(*h*) *The irreversible anomalous current.*

This is usually considered a characteristic property of liquid dielectrics, though in certain cases it has been reported as existing in solids, e.g. paper. It is quite likely that in such cases an absorbed liquid was the cause of the phenomenon.

Comparatively little work has been done on this section of the subject in recent years, though it has an extensive literature published mostly before 1913. Schweidler in Graetz's Handbuch * has summarized the results obtained up to 1912 as follows :—

"The decrease of current with time is often very slow. In general the higher the applied voltage or field strength, the earlier is the final steady value of the current reached. If after the current has flowed for a long time under an applied voltage E_1, this is reduced to a smaller value E_2, then after the first decrease in current corresponding to the sudden drop in voltage, there follows an increase of current.

"The law generally given for the time variation of the anomalous current is :—

$$i_2(t) = Bt^{-m}$$

i.e. the same law as for the reversible anomalous current characteristic of solids.

"The usual assumption that the constant final value a of the charging current is a normal conduction current and that the variable part $i_2(t)$ is an anomalous current superposed upon it, is negatived by the fact that this constant final value shows a so-called deviation from Ohm's law. When different voltages are used the final value a, in géneral, is not proportional to E but increases more slowly than E; in many cases as the voltage is further and further increased a "saturation" value of the current is reached, as in the case of ionized gases. In a few cases, however, the opposite holds and the quotient a/E increases with increasing voltage.

"As in the case of electrolytic conduction, the current increases strongly with temperature.

"When the two electrodes are of different form the phenomenon is apt to show a dissymmetry with respect to the direction of flow of current."

A long list of references is given by Schweidler in support of these statements.

The most important recent work on the subject is that of Tank.† He examined a number of liquids, viz. carbon bisulphide, turpentine, resin oil, benzol, petroleum, and found that they all showed the same phenomenon. Under a constant applied voltage the liquids passed a current which can be represented *approximately* by the formula

$$i = Bt^{-m} \text{ where } o < m < 1.$$

The current was measured by the simple galvanometer circuit over the range $t = 1$ to 30 minutes. Although the current was not reversible there were in certain cases traces of back-effect. The phenomenon is considered to be due to conduction by ions and this conduction is considered not to be a characteristic property of the insulator itself, but to depend largely on impurities. The traces of back-effect found in certain cases were considered to be due to chemical polarization of the electrodes.

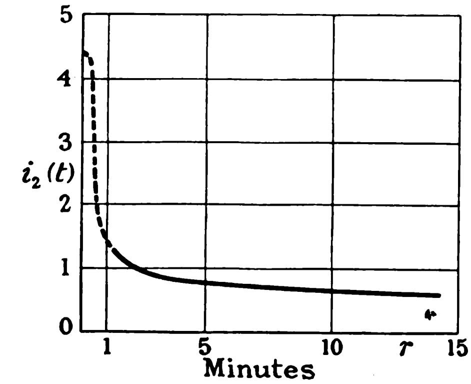

FIG. 9.—Variation of anomalous current with time in liquid dielectrics.

In the case of solids, which show the reversible anomalous phenomena, Tank found that the law $i_2(t) = Bt^{-m}$ held approximately, even when the time intervals were made as small as possible by means of the Helmholtz pendulum. When the liquids were examined in this way an important difference was noted. As the time t was made smaller and smaller the anomalous conduction current did not continue to increase at the rate indicated by the formula, but approached a constant value. The variations of the current with time appear to be as in Fig. 9. The experiments with short time intervals indicated a constant current. Those with $t > 1$ minute gave a variation

$$f(t) = Bt^{-m}$$

Unfortunately, it was not possible to investigate the intermediate portion of the curve. The dotted line in Fig. 9 indicates its probable course. Tank argued that when the current is alternating the conditions are such as correspond to the very small values of t, and to this alternating current the dielectric liquid will behave as if it has constant conductivity G. Thus the power loss will be given by V^2G and will be independent of the frequency. G must, of course, be calculated from the initial current when constant voltage is applied. Direct measurements of the power loss at 50 ∼ were found to agree with the value calculated from the constant-voltage experiments.

It seems, however, very doubtful whether we can

* GRAETZ : *Handbuch der Elektrizitat und des Magnetismus*, vol. 1, p. 237.
† TANK : *Ann. der Physik*, 1915, vol. 48, p. 307.

accept this as a law holding for liquid dielectrics. In the first place it assumes that the initial current is proportional to the applied voltage, and also that it does not depend on whether this voltage is increasing or diminishing so long as it is alternating at least several times per second. The results of previous observers quoted by Schweidler seem to indicate that neither of these assumptions is in general true.

On the whole the laws of the behaviour of liquid dielectrics under constant applied voltages do not as yet seem to be sufficiently generalized to enable us to state their connection with the power losses in alternating fields with any degree of exactness.

It seems to be the general opinion that—

(i) The anomalous phenomena in liquid dielectrics are due to conduction by ions.

(ii) That those phenomena depend enormously on impurities in the liquid.

(iii) If perfectly pure liquid dielectrics could be obtained they would probably be free from anomalous effects.

It is proposed to consider the ionic theory in detail later.*

III. The Methods of Measurement of Power Loss.

The methods of measuring the power dissipated in a dielectric when it is under the action of alternating voltage may be classified as follows :—

Wattmeter methods.

The power expended in any particular case may be directly measured by means of a wattmeter, either of the dynamometer or of the electrostatic type.

Calorimetric methods.

The quantity of heat generated in a given time in the dielectric as a result of the application of a known voltage to the condenser, is determined by placing the condenser in a calorimeter and making observations of rise in temperature.

Equivalent capacity and resistance methods.

The combination of perfect capacity and non-reactive resistance, which is equivalent to any particular condenser, is determined for the particular frequency chosen and the power factor or total power loss is then calculated as indicated in Section I. These methods may be divided into three classes :—

(i) Bridge methods—used mainly at power and telephonic frequencies.
(ii) Resonance substitution methods—widely used at radio frequencies.
(iii) Differential transformer methods.

Wave-form methods.

The actual wave-form and phase relationship of the applied voltage and current through the condenser are determined by means of an oscillograph of some type or other. The power factor or power loss is obtained from the records as indicated in Section I.

(*a*) *Wattmeter methods.*

The difficulties encountered in these methods depend on the fact that the power to be measured is usually quite small, and the power factor is also small. Thus a very sensitive wattmeter is necessary, and phase angle errors in the potential circuit are of great importance when a dynamometer is used. Allowance must also be made for the power expended in the current coil of the wattmeter, since this is also measured by the instrument. Rosa † has given a number of methods of using a dynamometer wattmeter for the measurement of dielectric losses. Fig. 10 (*a*) shows the connections for the simple deflection method, and Fig. 10 (*b*) is the corresponding vector diagram. OA represents the applied voltage V, OB represents i_p the current in the potential circuit, and thus α is the phase angle of this circuit, OG = i_c is the current in the current coil of the wattmeter, and therefore, in the condenser. If the current coil of the wattmeter had no resistance then OF would have represented the condenser current, where

$$\beta = \text{arc tan } rC\omega$$

and $\omega = \pi \times$ frequency,
r = resistance of wattmeter current coil,
C = capacity of condenser.

ϕ is the true phase angle of the condenser. The wattmeter reading is evidently proportional to ϕ' where

$$\phi = \phi' - \alpha + \beta$$

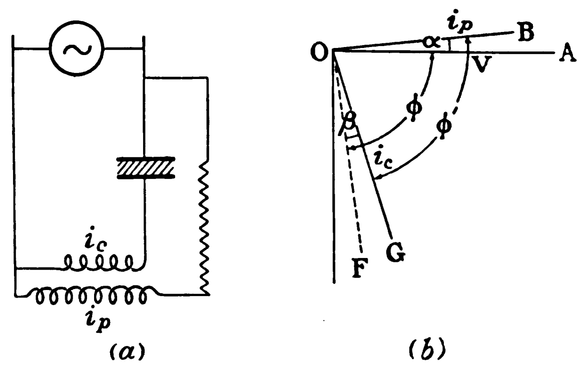

Fig. 10.—Vector diagram and connections of wattmeter.

Thus, in order to use this method, the corrections represented by α and β must be calculated from the constants of the wattmeter. It is difficult to obtain stability in an instrument which is made to have very great sensitivity, and thus Rosa has described a series of null methods in which such great stability is not necessary. In the simplest case a variable self-inductance is put in the potential circuit, and thus the angle α varied until ϕ' is 90°, i.e. the deflection is zero. Evidently the power factor (cos ϕ) can then be calculated from the known constants of the instrument and the added inductance. In other cases a compensating coil magnetically equivalent to the main wattmeter coil was wound over the latter. Current is passed through the compensating coil from a suitable shunt, or a transformer arrangement in the main circuit, and this auxiliary current adjusted until zero deflection is obtained as before. For details the original paper should be consulted. Rosa and Smith † have also described a resonance method using a dynamometer wattmeter. A

* Weissenberger: *Ann der Physik*, 1916, vol. 49, p. 481; Schrader: *Phys. Rev.*, 1921, vol. 17 (Ref. L/T2).

* Rosa: *Bulletin Bureau of Standards*, 1905, vol. 1, p. 383.
† Rosa and Smith: *Phys. Rev.*, 1899, vol. 8, p. 1.

self-inductance coil is placed in series or in parallel with the condenser under test, and the total power dissipated is measured by means of the wattmeter. These resonance methods are useful in special cases, e.g. in the series arrangement the voltage on the condenser may be very large, whilst the wattmeter only has to deal with small voltages.

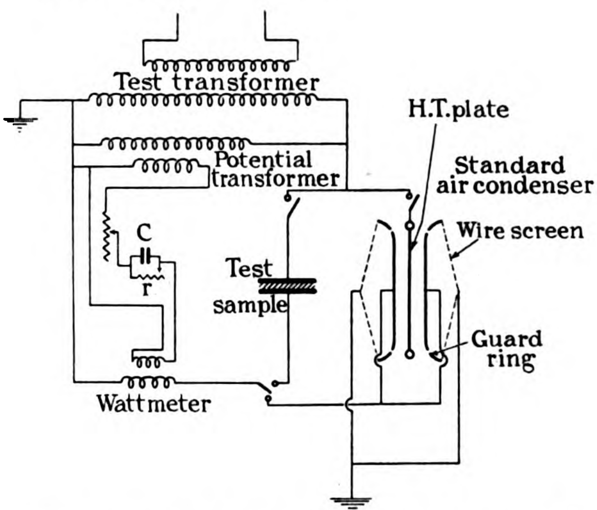

FIG. 11.—Shanklin's wattmeter method for power loss measurements.

In the majority of cases in which a dynamometer wattmeter has been used for dielectric loss measurements the instrument has been used deflectionally, and the phase-angle correction has been made by substituting an air condenser (assumed to be perfect) for the dielectric under test, and adjusting some part of the circuit

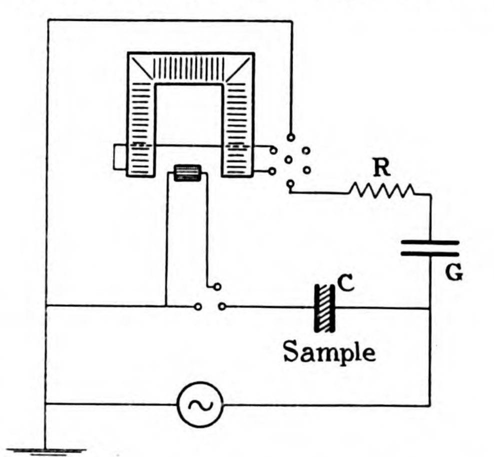

FIG. 12.—Tank's wattmeter method for power loss measurements.

until zero reading has been obtained on the wattmeter. The arrangement used by Shanklin * is shown in Fig. 11. The phase-angle compensating arrangement consists of a condenser C shunted by a variable resistance r, inserted in the potential circuit of the wattmeter. The standard air condenser is formed of three plates. The centre plate is at high voltage and is suspended from the ceiling by insulating cord. The outer plates are provided with guard rings, which are earthed, and all edges are rounded to avoid brush discharges. Air gaps up to 14 inches were used, the capacity being then 100 $\mu\mu$F. The power losses were considered negligible up to 60 000 volts. A similar arrangement is also used by Messrs. Brown Boveri,* but in this case the phase-angle adjustment was made by means of a variable self-inductance placed in the potential circuit of the wattmeter. In addition a correction was made for the effect of mutual inductance between the two wattmeter coils. For this purpose a special variometer was made, the coils of which were exactly the same as those of the wattmeter. This was connected in series with the wattmeter, in such a manner that the mutual inductance effect was in the opposite direction, so that if the variometer was turned in each case so that its reading was equal to the wattmeter reading, the mutual inductance effect would be compensated.† In order to get sufficient sensitivity an iron-cored wattmeter was used. Tank ‡ has also used a dynamometer with an iron core for dielectric loss measurements. In this case the instrument was a Sumpner dynamometer used as a wattmeter

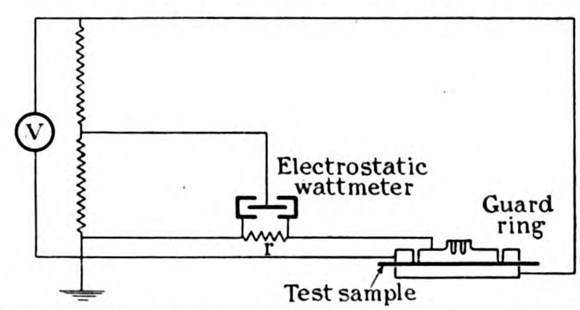

FIG. 13.—Rayner's electrostatic wattmeter method for power loss measurements.

(see Fig. 12). The auxiliary condenser G was adjusted so as to give resonance in the magnet circuit, and the accuracy of this adjustment was tested by substituting a perfect air condenser for the condenser under test, C, and adjusting until the deflection was zero. This arrangement is of course only for low voltages.

The electrostatic wattmeter has been used for the measurement of dielectric losses by a number of investigators, including Miles Walker,§ Skinner,|| Addenbrooke,¶ and Rayner.** The circuit used by Rayner is shown in Fig. 13. A guard-ring electrode was used so as to avoid measuring the losses due to ionization of the air at the edges of the electrode. The wattmeter was used with the voltage between needle and quadrants one half of that on the material under test. This avoids the correction for the energy loss in the current resistance *r*, which is necessary when the instrument is used in any other way. Measurements were made at voltages of the order 10 000.

* SHANKLIN: *Gen. Elec. Rev.*, 1916, vol. 19, p. 842.

* *Brown Boveri Review*, August, 1923.
† A. ROTH: *Archiv. für Elektr.*, 1917–18, vol. 6, p. 388.
‡ TANK: *Ann. der Physik*, 1915, vol. 48, p. 307.
§ MILES WALKER: *Trans. A.I.E.E.*, 1902, vol. 19, p. 1035.
|| SKINNER: *Ibid.*, p. 1047.
¶ ADDENBROOKE: *Electrician*, 1900, vol. 45, p. 901.
** RAYNER: *Journal I.E.E.*, 1912, vol. 49, p. 3.

Skinner * has worked at voltages up to 70 000, using an electrostatic wattmeter filled with oil. In this case the quadrants were 16 inches diameter and 7·5 inches high, and the needle was provided with a bifilar suspension. The needle became unsteady when the voltage was raised above 70 000. In all these cases the electrostatic wattmeter has been used deflectionally. It may also be used as a null instrument,† though it does not appear to have been used to any extent in this way for dielectric loss measurements.

The wattmeter method has not been successfully applied at radio frequencies owing to the great difficulties encountered. Alexanderson ‡ has, however, used the voltmeter-ammeter method. His arrangement is shown in Fig. 14. The method is designed to work at high voltages, and for this purpose a special air-core transformer was used. The primary P was excited by means of a high-frequency alternator. The secondary is shown in three sections, S_1, S_2, S_3. These actually formed one long coil which was built up by connecting a number of flat coils in series. The secondary terminated in two

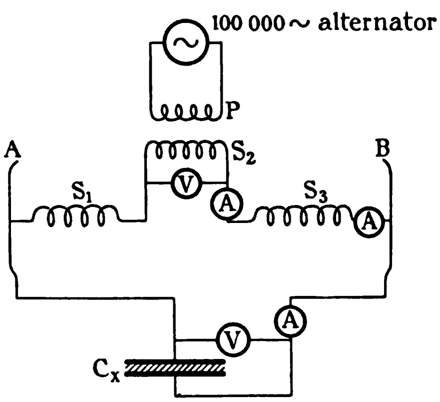

FIG. 14.—Alexanderson's method of measuring power loss at radio frequencies.

terminal shields, A and B, consisting of spirals of heavy copper wire. These are designed to avoid the production of large voltage gradients in the space occupied by the coils. The sample to be tested, C_x, was immersed in oil and connected across the terminal shields as shown. The actual power measurement was made by adjusting the secondary circuit to be in resonance, so that its power factor becomes unity, and then taking readings of current and voltage. Such a measurement was made with the sample disconnected, and then the sample was connected up and another set of observations taken. In each case, of course, resonance was obtained, so that the product volts × amperes gives the power dissipated in the circuit, including the transformer. The difference between the values obtained by the two sets of measurements was taken as the power dissipated in the dielectric. Exact details of the manipulation of the apparatus are not given. It is stated that the electrostatic voltmeter was often unreliable at high voltages, owing to corona. In such cases the voltage was calculated from the value of the current, self-inductance, and frequency.

* SKINNER : *Journ. Franklin Inst.*, 1917, vol. 183, p. 667.
† See Ref. L/A/T52, p. 3.
‡ ALEXANDERSON : *Proc. Inst. Rad. Eng.*, 1914, vol. 2, p. 137.

(*b*) *Calorimetric methods.*

Calorimetric methods are not often used when accurate measurements of power loss or power factor are required, as the measurements are difficult, take a great deal of time, and require very specialized apparatus. As the actual power dissipated must be sufficient to cause a measurable rise of temperature, these methods are only suitable when the power loss is large, i.e. with high voltage gradients, or high frequency. For rough, comparative measurements, thermal methods are often very convenient, e.g. two similar condensers may be compared by subjecting them to the same voltage and noting the rise of temperature in each case. More accurate measurements have been made by Rosa and Smith * and Granier.† Rosa and Smith * used a continuous-flow calorimeter. The condensers were placed between copper sheets, to which were soldered coiled copper pipes, the whole being blackened. Water flowed through the pipes and so carried away the heat developed in the condensers. The calorimeter containing this arrangement was provided with triple walls, and the cooling correction was eliminated by heating the space between the walls electrically, so as to keep its temperature the same as that of the calorimeter, this equality of temperature being indicated by a differential air thermometer. The temperature of the water at inlet and exit was measured by accurate thermometers and the power dissipated as heat was calculated from the rate of flow of the water, and the difference between these two temperatures. The current and voltage were also measured and thus the power factor was calculated. These measurements were made at power frequencies, and the power dissipated was of the order of 10 watts. The power factors measured varied from about 0·5 per cent to 3 per cent. Granier † made measurements at high frequencies, 1 000 ~ to 300 000 ~. The dielectrics investigated were in the form of flexible sheets, which were wound on to a brass tube. Over the dielectric were wound :—

1. A layer of tin-foil to serve as the second electrode.
2. A coil of insulated wire of a few ohms resistance.
3. A layer of dry silk.

The whole was then placed in a vacuum flask in order to reduce the cooling correction to a minimum. The temperature-rise was measured by means of a thermometer inside the brass tube (and thus not in the electric field). In order to equalize the temperature, the tube was half filled with water or petrol. The procedure was as follows :—

High-frequency current was passed through the dielectric, and the current and voltage were measured (the current by means of a thermo-junction and galvanometer calibrated at 900 ~, and the voltage by an electrometer). The rise in temperature in a given time was noted. Direct current was now passed through the auxiliary coil wound over the dielectric, the value being so adjusted that the rise in temperature was practically the same at the same time. The current, voltage and actual temperature-rise were again noted. In the d.c. experiment let V_1, I_1 and Δt_1 be the voltage,

* ROSA and SMITH : *Phys. Rev.*, 1899, vol. 8, p. 79.
† GRANIER : *Bull. de la Soc. Française des Électriciens*, 1923, vol. 3, p. 333.

current and temperature-rise respectively. Let V_2, I_2, Δt_2 be the corresponding a.c. values. Then we have

$$\text{Power factor} = \frac{V_1 I_1 \times \Delta t_2}{V_2 I_2 \times \Delta t_1}$$

the time interval was, of course, the same for each experiment. The temperature-rise measured was 0·1 to 1 deg. C., and the power factors varied from 0·002 to 0·2.

(*c*) *Equivalent resistance and capacity methods.*

(i) *Bridge methods.*—These are used mainly at power and telephonic frequencies, though they can be used at radio frequencies.* A simple Wheatstone network is generally used (see Fig. 15). Here the test sample is in arm 1 of the bridge, and it is compared with a standard condenser in arm 2. The power factor of the material under test may be balanced by a variable resistance in series with the standard condenser, as in

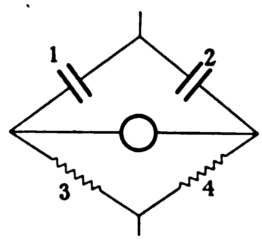

FIG. 15.—Wheatstone's bridge.

the Wien bridge, or if the power factor is very large, it may be convenient to place a variable resistance in parallel with the standard condenser. Another very convenient power-factor adjustment is that used in the Schering bridge, in which the ratio arms 3 and 4 are non-inductive resistances, and a variable capacity in parallel with arm 4 balances the power factor of arm 1 (Fig. 16). The ratio arms 3 and 4 may be non-inductive resistances, condensers, or inductances. In any case it is desirable that their phase angles should be equal. For the most precise measurements a symmetrical bridge is used, i.e. the ratio arms are equal, and a substitution method is employed.† In this way errors due to earth capacities and small residual errors in the phase angles of the ratio arms are avoided. The effects of earth capacities should be reduced to a minimum by earthing a suitable point on the bridge, or by using the Wagner earthing device. A general discussion of the various bridges, with practical details of earthing devices, etc., has been given by the author,‡ so that here only a few special cases will be considered. The Schering bridge § (Fig. 16), previously mentioned, may be considered as a typical case, since it is equally useful for power and telephonic frequencies, and for low and high voltages. The detector D may be a telephone or vibration galvanometer depending on the frequency.

* ENGLUND: *Proc. Inst. Rad. Eng.*, 1920, vol. 8, p. 326. HART: *Journal I.E.E.*, 1923, vol. 61, p. 697.
† GIEBE and ZICKNER: *Archiv. für Elektr.*, 1922, vol. 11, p. 109.
‡ HARTSHORN: *Beama Journal*, 1923, vol. 13, p. 89.
§ SCHERING: *Zeits. für Instr.*, 1920, vol. 40, p. 124; *Semm. Archiv. für Elektr.*, 1920, vol. 9, p. 30.

The ratio arms r_3 and r_4 are non-inductive capacity resistances whose impedances are very small compared with those of the capacities C_1 and C_2. Thus the point B of the bridge should be earthed, since then the detector will always be nearly at earth potential, and earth effects will not seriously affect it. On account of the high impedances of C_1 and C_2, the resistances r_3 and r_4 do not carry large currents, even when the voltage is very high, and thus no very special design is necessary, and further the bridge consumes very little power. The standard condenser C_2 has to withstand practically the whole applied voltage, and, by using a condenser of suitable design, measurements have been made on this bridge with voltages up to 100 kV. In this case the adjustments are made on r_3 and C_4, both of which are always nearly at earth potential and thus may be adjusted quite safely. A spark-gap across r_3 protects the system against damage

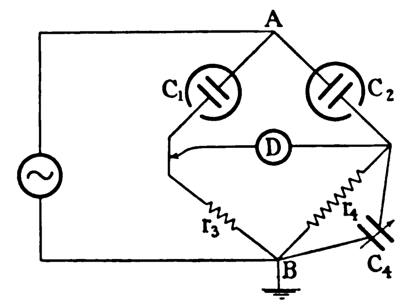

FIG. 16.—Schering bridge.

due to breakdown of the test condenser C_1. The equations of balance are

$$\tan \delta_1 = r_4 C_4 \omega$$
$$C_1 = \frac{r_4}{r_3} C_2 \cos^2 \delta = \frac{r_4}{r_3} C_2 \text{ (approx.)}$$

In practice it is convenient to keep r_4 constant, since then the bridge may be made direct reading for power factor, e.g. in work at 50∼, give r_4 a value of

$$\frac{1\,000}{\pi} \text{ ohms}$$

then $\tan \delta = 10^5 C_4$, and thus the power factor (approximately equal to $\tan \delta$) is equal to one-tenth of the reading of C_4 in microfarads. For fine adjustments of r_3 it is convenient to use a low-resistance slide wire between C_1 and r_3 as shown, the galvanometer being connected to the sliding potential point. This eliminates any trouble due to variable contact resistance. For measurements with low voltage at telephonic frequency it is often convenient to keep both r_3 and r_4 fixed and to vary the standard air condenser C_2. A modification * of the Schering bridge for dealing with large capacities (e.g. long lengths of cable) at high voltages has also been published. In this case the resistance r_3 may have to carry a large current, and since it must be capable of fine adjustment, its construction presents difficulties. In such cases the arrangement shown in

* SCHERING: *Zeits. für Instr.* 1924, vol. 44, p. 98.

Fig. 17 is used. The resistance r_3 is replaced by a parallel combination, consisting of a fixed small resistance n, a fixed resistance r, a slide wire S, and a variable resistance ρ. The galvanometer is connected to the sliding potential point as in the previous arrangement. Thus the small fixed resistance carries the greater part of the current, and the high resistances in parallel, which carry but a small current, are capable of fine adjustment quite conveniently. The formulæ for this arrangement are

$$C_1 = C_2 R_4 \frac{n + r + S + \rho}{n(\rho + \sigma)}$$

$$\tan \delta = \omega R_4 C_4 - \left[\frac{r + S - \sigma}{\rho + \sigma} R_4 \omega C_2\right]$$

The term in brackets is negligibly small, so that the original formula for tan δ holds.

Rosen * has used the Wien bridge for high-voltage measurements, the voltage being applied across the ratio arms. This necessitates special design of the

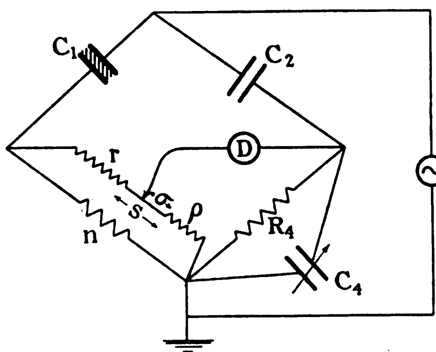

FIG. 17.—Schering bridge for high charging currents.

resistance arms which must carry heavy currents, but allows of the use of a low-voltage standard condenser.

In attempting to use bridge methods at radio frequencies, the difficulties encountered are considerably greater than at telephonic frequencies. A simple telephone receiver can no longer be used as a detector. It is necessary to use also an auxiliary heterodyne oscillator, with an amplifier to give the necessary sensitivity. Detecting arrangements on these lines are described by Englund † and Hart.‡ Hart varied the capacity in the heterodyne oscillator circuit, and listened for a change of frequency in the beat note, which must occur when the bridge is out of balance. Englund, on the other hand, obtained a beat note of constant frequency, and adjusted the bridge until the sound became of minimum intensity. Hart used the simple Wien bridge, with resistances formed of long straight wires, and a standard air condenser. The corner of the bridge at which the adjustments were made was earthed. The bridge described by Englund as being in use in the Western Electric Company's laboratories, has two equal ratio arms (non-reactive coils of 500 ohms). The third arm consists of a variable self-inductance in series with a standard variable air condenser, and the fourth arm is another non-reactive resistance. The coil and condenser in the third arm are adjusted to be in resonance at the frequency used, and thus the impedance of this arm becomes low, and the whole arrangement becomes a low-impedance bridge. Any given condenser is tested by substitution against the standard condenser.

The great advantage of bridge methods is that fluctuations in the applied voltage are of less consequence than in the other methods; the balance point is usually practically independent of the voltage.

(ii) *Substitution in a circuit adjusted to resonance.*—This method is the one generally used at radio frequencies on account of the simplicity of the circuit. General discussions of such methods are given by Dellinger * and Dye.† The arrangement of the measuring circuit is as shown in Fig. 18. L is a self-inductance, C a standard variable air condenser, C_x the condenser to be tested, r a non-inductive resistance, and A a current-indicating instrument, e.g. a thermo-junction and galvanometer. This circuit is loosely coupled to an oscillating circuit which supplies the power. In the simplest substitution method, the test condenser is

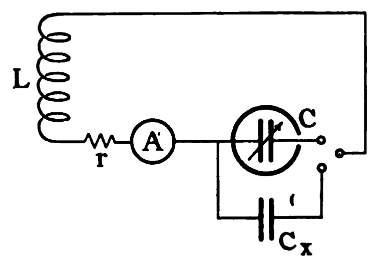

FIG. 18.—Power loss measurements at radio frequencies by simple substitution.

first placed in circuit, the resistance r being removed, and the resonance adjustment is made. The current reading is then noted, C_x is disconnected, and C substituted for it. The value of C is adjusted until resonance is again obtained, and the value of r is varied until the current is the same as before. The readings of r and C then give the equivalent series resistance and capacity of the test sample (assuming the standard condenser C is perfect). It is essential that the voltage induced in the measuring circuit should be the same before and after the substitution, and it is of the greatest importance that the capacity coupling between the generating and measuring circuits should not be altered in making the substitution. The difficulties of satisfying such conditions are generally considered to make this simple method rather inaccurate, though Schott ‡ favours this method for precision measurements. The resistances r usually consist of straight thin wires provided with thick copper terminal pieces, which dip into mercury cups. A series of such resistances all of the same length but of different resistances is convenient. For very fine adjustments of resistance, Schott used an arrangement like a variometer, the movable coil being wound of high-resistance wire, and short-circuited in

* ROSEN: *Proc. Phys. Soc.*, 1923, vol. 35, p. 235.
† ENGLUND: *Proc. Inst. Rad. Eng.*, 1920, vol. 8, p. 326.
‡ HART: *Journal I.E.E.*, 1923, vol. 61, p. 697.

* DELLINGER: *Proc. Inst. Rad. Eng.*, 1919, vol. 7, p. 27.
† DYE: "Glazebrook's Dictionary of Applied Physics," vol. 2, p. 675.
‡ SCHOTT: *Jahrbuch der Drahtlosen Teleg.*, 1921, vol. 18, p. 82.

itself. The effective resistance of this arrangement varies with the position of the moving coil, and thus a continuous fine adjustment of resistance is possible. It is necessary to calibrate the arrangement against the straight-wire standard resistances for each frequency used. As current indicator Schott used a thermo-junction and galvanometer, placed in a separate circuit (aperiodic), coupled with the measuring circuit. By means of a potentiometer arrangement the galvanometer deflection was reduced to zero for the required current. This arrangement was considered greatly to increase the sensitivity.

For accurate measurements this simple substitution method is not generally used, but the following procedure is adopted. C_x is inserted, the resonance adjustment made, and the current reading noted. This is repeated for various values of r, and from the observations, the total effective resistance of the circuit is calculated using the formula

$$I = \frac{E}{R + r}$$

where E is the induced e.m.f. (which is unaffected by changing r) and R is the effective resistance of the whole circuit excluding r. The standard condenser is now substituted for C_x and the experiment repeated. The difference between the two values of R gives the effective resistance of the test condenser, and its capacity is given by the reading of the standard condenser. Alterations of capacity coupling due to the substitution of the standard condenser will obviously cause no error when this method is used. It is important to avoid reaction between the measuring and generating circuits, and the resistances r and the detector should be connected to the shield side of the condenser which may be earthed.

Dielectric loss measurements by the substitution method at radio frequencies have also been made by Fleming and Dyke,* L. W. Austin,† G. E. Bairsto,‡ and Dellinger and Preston.§ Bairsto used a rotating commutator for making the substitution of one condenser for the other, rapidly and continuously, each condenser being in circuit for equal time intervals. He had a thermo-junction in series with each condenser, and the two were adjusted to equal sensitivity and connected differentially to a galvanometer. Thus the method became a null method. The necessity for this arose from the fact that an arc was used as generator, and thus there were fluctuations of voltage. Bairsto's resistance adjustment was made by means of a variable water resistance in parallel with the standard air condenser.

(iii) *The differential transformer method.*‖—This method has also been used for radio-frequency measurements. The principle is shown in Fig. 19. The differential transformer possesses one secondary S and two primaries P_1 and P_2 exactly the same in every respect, except that they are wound in opposite directions. The test condenser C_x is in series with one primary, and the standard variable air condenser C and resistance r are in series with the other. Current is passed through the two primaries in parallel as indicated in the diagram. It is obvious that when the condenser C and resistance r are equivalent to C_x, then the current through both primaries will be the same in magnitude and phase, and the net induced current in the secondary S will be zero. Thus the experiment consists in adjusting r and C until this condition is established. The detector used by Hund is shown in Fig. 19. It consists of two thermo-junctions T_1 and T_2 connected in a bridge network with equal resistance ratio arms: B_1, B_2, B_3, B_4 are blocking condensers. The current from the secondary of the transformer is led into two opposite corners of the bridge as shown. An auxiliary current obtained by coupling on to the main circuit is passed into the other two opposite corners of the bridge. It can be shown that the galvanometer G measures the scalar product of these two currents. Thus it not only indicates when the current in the secondary S becomes

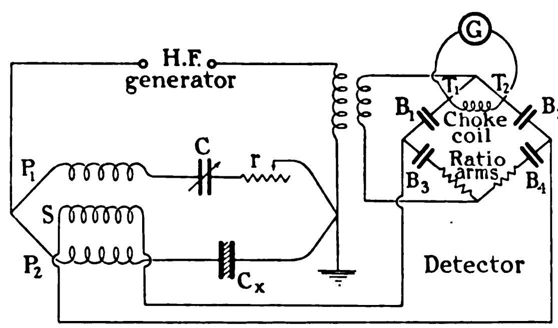

FIG. 19.—Use of differential transformer in high-frequency power loss measurements.

zero, but by changing the phase of the auxiliary current the arrangement can be made sensitive to changes of C or to changes of r, thus making the two adjustments to a certain extent independent. Trautwein * has made a detailed study of the differential transformer method, which he considers superior to all other methods at radio frequencies. He discusses the sensitivity, the means of changing the phase of the auxiliary current, and various forms of detector for measuring the scalar product of two currents. For this purpose instead of the thermo-junction arrangement he has used, (1) a string electrometer, (2) an arrangement of two diodes or two triodes with a differential galvanometer.

(*d*) *Wave-form methods.*

This method in its simplest form has been used by Thornton.† He made up large condensers, using a number of sheets of dielectric with tin-foil electrodes, the whole being under pressure. Alternating current of frequency 38 ∼ was passed through these, and the wave-form of current and voltage recorded by means of an electromagnetic oscillograph. From the records, "hysteresis" loops were obtained and power factors calculated as described in Section I.

The same method has been used at very low frequencies (of the order of 1 cycle per second) by Granier.‡

* FLEMING and DYKE: *Proc. Phys. Soc.*, 1910, vol. 23, p. 117.
† AUSTIN: *Bulletin Bureau of Standards*, 1913, vol. 9, p. 73.
‡ BAIRSTO: *Proc. Roy. Soc.*, 1920, vol. 96, p. 363.
§ DELLINGER and PRESTON: *Technological Papers, Bureau Standards*, No. 216, vol. 16, p. 502.
‖ HUND, A.: *Electrician*, 1915, vol. 74, p. 458.

* TRAUTWEIN: *Jahrb. der drahtl. Teleg.*, 1921, vol. 18, p. 261.
† THORNTON: *Proc. Phys. Soc.*, 1912, vol. 24, p. 301.
‡ GRANIER: *Rev. Gén. de l'Électricité*, 1921, vol. 10, p. 219. *Bull. de la Soc. Française des Élect.*, 1923, vol. 3, p. 355.

He used a number of different arrangements. In some cases, by means of a rotating contact device, the condenser was discharged through a ballistic galvanometer or fluxmeter, at some definite point on the cycle. Thus the cycle of quantity of charge and voltage was plotted by taking readings for a number of points round the cycle. It is, of course, necessary to short-circuit the condenser for some time between observations. In other experiments, a galvanometer was used as an oscillograph for very low frequencies. This is, of course, essentially the same as Thornton's method. A point-to-point method using an electrometer is also described,

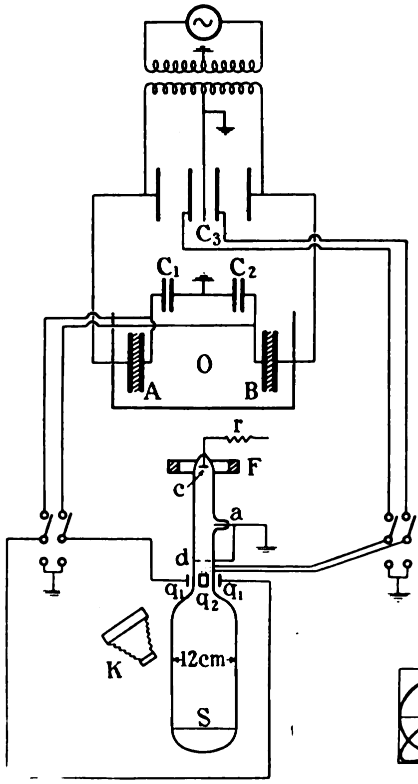

FIG. 20.—Use of cathode-ray oscillograph in power loss measurements.

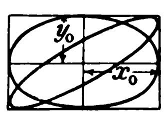

FIG. 21.—Cyclogram from cathode-ray oscillograph.

but none of these very low-frequency methods are very convenient, and the interpretation of the results is a matter of extreme difficulty. Minton * has described the application of the cathode ray oscillograph to measurements of this kind. The arrangement is shown in Fig. 20. C is the cathode, and a the anode, and when the tube is working there is a potential difference of 20 000 volts between the two. The cathode rays pass through a small hole about 0·8 mm diameter in the diaphragm d. The small pencil of rays so obtained falls on the fluorescent screen S, and produces a luminous spot at the point of impact.

There are two pairs of deflecting plates q_1q_1, and q_2q_2, between which the cathode rays pass. Plates q_1q_1 are parallel and at right angles to q_2q_2, which are also parallel. The insulating material under test was made up into two equal condensers A and B, and as the tests were made at high voltages these were placed under oil in the box O. C_1 and C_2 are two air condensers in series with A and B. The potential difference across C_1 and C_2 is proportional to the current through the specimens, and is applied to the plates q_1q_1. C_3 is also an air condenser and the potential difference across it is proportional to the applied voltage. This potential difference is applied to the other pair of plates q_2q_2. Let the voltage applied to the test system AC_1C_2B be

$$v = V_0 \sin \omega t$$

Then the current will be

$$i = I_0 \sin (\omega t + \phi)$$

where ϕ is the phase angle of the system. The deflection produced by plates q_1 is

$$x = k_1 I_0 \cos (\omega t + \phi)$$

where k_1 is a proportionality constant. That produced by plates q_2 is similarly

$$y = k_2 V_0 \sin \omega t.$$

When these operate simultaneously the image on the screen is an ellipse as in Fig. 21. The area of this ellipse is given by

$$A = \int_0^{2\pi} y dx = \pi k_1 k_2 V_0 I_0 \cos \phi$$

If the two deflections are allowed to take place separately, straight-line images are obtained of lengths

$$2x_0 = 2k_1 I_0 \quad \text{and} \quad 2y_0 = 2k_2 V_0$$

Thus the area A is given by

$$A = \pi x_0 y_0 \cos \phi$$

and $\cos \phi$ may be determined by measuring A, x_0 and y_0. For any given set-up of the apparatus, the power factor ($\cos \phi$) is evidently proportional to the area of the ellipse obtained. The images were photographed by means of the camera K. The power factor so measured is that of the test system AC_1C_2B. The power factor of the dielectric itself, i.e. A and B, was calculated from this as follows :—

The voltage e_1 across C_1 and C_2 was measured by means of an electrostatic voltmeter. The total applied voltage V was also measured (by reading the voltage on the low-tension side of the transformer and multiplying by the ratio of transformation). It is easy to show that the actual voltage across the insulator A and B is

$$E' = \sqrt{V^2 + e_1^2 - 2Ve_1 \sin \phi}$$

and that the power factor of the insulation ($\cos \phi'$) is given by

$$\cos \phi' = \cos \phi + \frac{e_1}{2E'} \sin 2\phi$$

This expression is an approximation which is accurate enough for practical purposes. The value of e_1, the potential difference across C_1 and C_2, together with the capacity value for C_1 and C_2 and the frequency, determines the current through the specimens. The voltage across them is also determined as mentioned above. Thus the total power loss can be calculated when the power factor is known.

* MINTON : *Trans. A.I.E.E.*, 1915, vol. 34 (2), p. 1627.

As regards the cathode-ray tube itself, it was found necessary to exhaust it for three or four hours at high temperature, say 350° C., in order to remove gas adsorbed on the walls. The vacuum then remained constant for two years or more. The accumulation of charges on the glass surrounding the cathode also caused trouble, and to avoid this it was sometimes preferable to exhaust at 350° C. for only half an hour. This leaves sufficient adsorbed gas to conduct away these charges, but not enough to spoil the vacuum for a long period. The deflecting plates were of brass and mounted outside the tube, using ebonite as insulator. To avoid any electrostatic shielding effect of moisture on the glass in the neighbourhood of the deflecting plates, the tube in this neighbourhood was coated with cellulose nitrate. As shown in the diagram, the record on the fluorescent screen is photographed at an angle. This does not introduce difficulties into the calculation of $\cos\phi$, since this is given as the ratio $A/x_0y_0\pi$, and both numerator and denominator are equally affected by taking the photograph in this way.

The chief feature of the cathode-ray oscillograph for measurements of this kind is that it can be used for high voltages and also for high frequencies.

(*e*) *The electrodes.*

In all methods of testing any given dielectric, it is necessary to provide it with two conducting electrodes. Liquids present no difficulty in this respect. In the case of solids, tin-foil has been widely used for making electrodes. Appleyard * first showed that when tin-foil is used, the values obtained for insulation resistance are very uncertain, due to the fact that tin-foil does not make proper contact with the dielectric. He found that mercury electrodes gave much more consistent results. Bairsto † made an investigation into tin-foil contact with dielectrics, and showed that, although tin-foil may give very inaccurate results for d.c. measurements, when a.c. measurements are made the error is only comparatively small. This is because the alternating current can pass through the large contact capacity instead of through the high contact resistance. In some cases,‡ to avoid this contact difficulty, the material has been tested in an air-gap, no attempt being made to secure metallic contact with the specimen. For certain conditions (high temperature, etc.), graphite has been used instead of mercury for electrode material. Schrader § found that he could get better contact with graphite than with mercury in certain experiments. In experiments on various kinds of glass, Schott ‖ used steel plates carefully ground flat and polished, as electrodes. The glass (in the form of flat plates) was also ground optically flat and polished, so that the glass and steel surfaces when brought together would give contact of a very high order. R. Jaeger ¶ in a series of experiments on the dielectric constants of solids, used electrodes of very thin foil (tin, silver, or platinum). Circular pieces were cut out and stuck on to the dielectric with water or oil of high dielectric constant. This, of course, increases the contact capacity, and so reduces the error due to imperfect contact. Attempts to measure the thickness of the oil film showed that it was less than 0·001 mm. Jaeger also used the air-gap method. The surfaces of such dielectrics as glass, mica, may be silvered, and this process has frequently been used for providing the material with electrodes.*

Cathodic sputtering has also occasionally been used, while H. J. McLeod † sprayed material with lead from an oxyhydrogen gun. Such methods are, of course, not very convenient when a large number of samples has to be tested. In testing flexible materials under more or less working conditions, it is convenient to wind the material tightly on to a brass rod, which forms one electrode, and then to wind tin-foil over the material to form the other. For work at high voltages, brass discs with carefully rounded corners are often used as electrodes ‡ (Fig. 13).

IV. Theories of the Anomalous Phenomena of Dielectrics.

Many theories have been proposed to account for the anomalous properties of dielectrics. The electron theory of the normal displacement can be regarded as fairly definitely established, and will not be considered here. The so-called anomalous phenomena—power loss in alternating fields and "absorption" in constant fields—alone will be dealt with. These will be considered as superposed upon the normal properties. In Section II it is shown that the laws of the power loss in alternating fields can be deduced from those of the polarization or current in constant fields, so that in considering any theory it is merely sufficient to explain one of those phenomena.

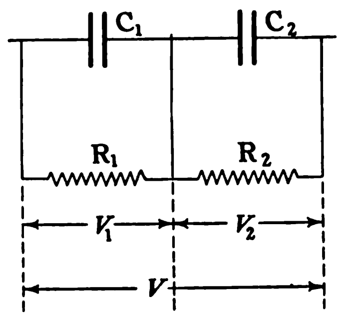

FIG. 22.—Representation of dielectric of laminated structure.

(*a*) *Maxwell's theory.*

Maxwell § showed that if the electrical behaviour of a dielectric can be represented by two constants, its specific resistance ρ and dielectric constant ϵ, then a *homogeneous* dielectric should be free from absorption. If, however, the dielectric be of heterogeneous structure and the product $\epsilon\rho$ be not the same for all the components, then absorption is a necessary consequence. It will also follow that when the condenser is subject to alternating voltage there will be a change of capacity with frequency, and a power loss greater than the

* R. Appleyard: *Proc. Phys. Soc.*, 1905, vol. 19, p. 724.
† Bairsto: *Proc. Phys. Soc.*, 1913, vol. 25, p. 301.
‡ A. Campbell: *Proc. Roy. Soc.*, 1906, vol. 78 p. 196. Dye and Hartshorn: *Proc. Phys. Soc.*, 1924, vol. 37, p. 42.
§ Schrader: *Electric Journal*, 1920, vol. 17, p. 157.
‖ Schott: *Jahrb. der Drahtl. Teleg.*, 1921, vol. 18, p. 82.
¶ R. Jaeger: *Ann. der Physik*, 1917, vol. 53, p. 408.

* See, for example, Poole: *Phil. Mag.*, 1917, vol. 34, p. 195.
† McLeod: *Phys. Rev.*, 1923, vol. 21, p. 53.
‡ Rayner: *Journal I.E.E.*, 1912, vol. 49, p. 3.
§ Maxwell: "Electricity and Magnetism," vol. 1, p. 328.

resistance of the whole structure to direct current might lead us to suppose.

Maxwell's exposition of his theory is not in the form most convenient for comparison with the results of recent measurements, and the theory has been developed in various directions by several workers. Rowland and Grover * have given its application to alternating currents. Wagner † has explained in simple terms the mechanism of absorption in such cases.

Meyer ‡ has given a restatement of the theory with special reference to dielectrics containing absorbed moisture, and in 1923 Steinmetz § gave another account of the theory with special reference to cables of laminated structure, together with a simple explanation of the mechanism of the action much the same as that of Wagner.

Following Meyer, consider the case of a dielectric of laminated structure composed of two substances. Take the simplest possible case of a parallel-plate condenser, the dielectric being formed of two layers, one of each of the components. Then the effect is the same as if we had two condensers in series, as in Fig. 22. Let C_1C_2 represent the capacities of these condensers and R_1R_2 their resistances. Let V_1V_2 be the differences of potential between their plates and V the potential difference across the whole condenser. The total current through the two component condensers is, of course, the same. Denote it by I. Then

$$I = \frac{1}{R_1}V_1 + C_1\frac{dV_1}{dt} \quad \text{and} \quad I = \frac{1}{R_2}V_2 + C_2\frac{dV_2}{dt}$$

$$\therefore\ V_1 = \frac{1}{C_1}e^{\frac{-t}{\tau_1}}\int_{-\infty}^{t} e^{\frac{-t}{\tau_1}} I dt$$

$$\therefore\ V_2 = \frac{C_1}{C_2}e^{\frac{-t}{\tau_2}}\int_{-\infty}^{t} e^{\frac{-t}{\tau_2}} I dt$$

where τ_1 and τ_2 are the relaxation times of the two components

$$\tau_1 = R_1C_1 = \frac{\epsilon_1\rho_1}{4\pi v^2}$$

These equations lead to the differential equation

$$\left(\frac{1}{C_1} + \frac{1}{C_2}\right)\frac{dI}{dt} + \left(\frac{1}{\tau_1 C_2} + \frac{1}{\tau_2 C_1}\right)I = \frac{d^2V}{dt^2} + \left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)\frac{dV}{dt} + \frac{1}{\tau_1\tau_2}V$$

The general solution is

$$I = C\frac{dV}{dt} + \frac{V}{R} + \frac{aC}{T}e^{\frac{-t}{T}}\int_{-\infty}^{t} e^{\frac{t}{T}}\frac{dV}{dt} \times dt$$

where
$$C = \frac{C_1C_2}{C_1 + C_2}$$
$$R = R_1 + R_2$$
$$T = \frac{(C_1 + C_2)R_1R_2}{R_1 + R_2}$$
$$a = \frac{(R_1C_1 - R_2C_2)^2}{C_1C_2(R_1 + R_2)^2}$$

* F. W. GROVER: *Bulletin Bureau of Standards*, 1911, vol. 7, p. 519.
† K. W. WAGNER: *E.T.Z.*, 1915, vol. 36, pp. 111, 121, 135, 163.
‡ U. MEYER: *Verh. Deutsch. Physik. Gesell.*, 1917, vol. 19, p. 139.
§ STEINMETZ: *A.I.E.E. Journal*, 1923.

The two cases of greatest interest are

Case I.—When a constant voltage E_0 is applied at the instant $t = 0$. We get

$$I = E_0\left[\frac{1}{R} + \frac{aC}{T}e^{\frac{-t}{T}}\right]$$

Thus superposed upon the constant leakage current E_0/R we have an absorption current

$$E_0 a\frac{C}{T}e^{\frac{-t}{T}}$$

The only case in which there is no absorption current is when $a = 0$, i.e. when $R_1C_1 - R_2C_2 = 0$, i.e. when $\epsilon_1\rho_1 = \epsilon_2\rho_2$.

Case II.—When alternating voltage is applied to the condenser. Putting

$$V = V_0e^{j\omega t}$$

we get

$$I = V\left[j\omega C + \frac{1}{R} + \frac{j\omega aC}{1 + j\omega T}\right]$$

Thus
$$\frac{\Delta C}{C} = \frac{a}{1 + \omega^2T^2}$$

giving the change of capacity with frequency, and

$$\frac{C + \Delta C}{C} \times \tan\delta = \frac{a\omega T}{1 + \omega^2T^2}$$

which determines the loss angle δ due to "absorption" only. There is, of course, additional power loss due to the resistance R.

It is to be noted that in this case the characteristic time function of the absorption current is

$$f(t) = e^{\frac{-t}{T}}$$

Thus according to the Superposition Principle,* the general equation of the absorption current is

$$i_2(t) = \beta C\int_{-\infty}^{t}\frac{dE(u)}{du}\cdot f(t-u)du = \beta C\int_{-\infty}^{t}\frac{dE(u)}{du}\cdot e^{\frac{-(t-u)}{T}}du$$
$$= \beta Ce^{\frac{-t}{T}}\int_{-\infty}^{t}\frac{dE(u)}{du}\cdot e^{\frac{u}{T}}du$$

This is obviously the same as the general expression given above for the absorption current if we put

$$\beta = \frac{a}{T}$$

Thus the theory can explain the Superposition Principle.

We have seen, however, that the function $f(t)$ as determined by experiment is not a simple exponential function. Thus the simple case considered is not sufficient to explain the results of experiment. The theory must obviously be extended to cases in which the dielectric is built up of several components. Meyer obtains the general solution in the case of a dielectric

* See Section II, p. 1162.

with three layers. In this case the absorption current is represented by the sum of two exponential terms, and similarly if we assume that the dielectric is built up of n component layers we obtain $n - 1$ exponential terms in the expression for the absorption current (see Steinmetz).* It is obvious that by taking a sufficient number of terms any experimentally-found curve can be represented, and thus by assuming sufficiently heterogeneous structure almost any experimental curve could be explained by this theory. Steinmetz* showed that in the case of one particular cable, two terms were sufficient to represent the curve actually obtained, and there is no doubt that the absorption current and power loss in dielectrics of laminated structure are at least in part due to the phenomena described by Maxwell's theory.

If the theory provided the complete explanation of the anomalous phenomena shown by dielectrics, we should expect that dielectrics such as quartz, iceland spar, rock salt and pure substances generally, where a homogeneous structure is to be expected, would be free from absorption, etc. However, as mentioned in Section II, Thornton † has observed the phenomena in crystalline quartz, both parallel and perpendicular to the optic axis, and also in fused quartz, whilst Richardson ‡ has found similar effects in iceland spar and rock salt as well as quartz. Both Thornton and H. A. Wilson § have observed absorption phenomena in sulphur. Thus it seems probable that Maxwell's theory does not provide a complete explanation of the anomalies, though it is certainly at least a partial explanation, in most commercial dielectrics.

(b) *Theories of dielectric hysteresis or viscosity.*

Maxwell's theory seeks an explanation of the anomalous properties of dielectrics in anomalies in structure. As this explanation seems hardly sufficient, a number of other theories have been put forward in which the anomalies were considered to be in the behaviour of the dielectric. The displacement is assumed not always to be a function of the field strength only, giving a constant dielectric coefficient, but to depend also on other conditions such as the previous state of the medium or the time rate of change of field strength. Sometimes it is assumed that there is a dielectric hysteresis effect analogous to magnetic hysteresis, i.e. a constant power loss per cycle depending only on the maximum value of the displacement, and not on the frequency. There seems to be, however, little, if any, evidence in support of this. The evidence is much more in favour of what may be termed viscous hysteresis. Theories on these lines are:—

(i) *Houllevigue's theory.*—See Grover.|| This assumes the displacement in an imperfect dielectric to consist of two parts: (1) an instantaneous displacement of the ether until the elastic forces between the ether and the molecules are in equilibrium; (2) an additional gradual yielding of the molecules under this tension, so that to the instantaneous displacement of the ether is added the displacement of the mean position of the molecules. The displacement of the molecules is assumed to be opposed by a frictional force proportional to their velocity, and this frictional force is the cause of the loss of power. Grover gives the mathematical development of the theory, but as the conclusions are not well supported by experiment and are not considered in most recent work, further detail is omitted here.

(ii) *Pellat's theory.**—Pellat's theory assumes that when a field of strength E_0 is impressed on a dielectric, the displacement instantaneously takes up the value

$$D_0 = \frac{\epsilon E_0}{4\pi v^2}$$

and then increases logarithmically towards a final value $(1 + \gamma)$ times as great,

$$\text{i.e.} \quad D_t = \frac{\epsilon E_0}{4\pi^2} + \frac{\epsilon E_0}{4\pi v^2}(1 - e^{-\alpha t})\gamma = D_0 + D_v \text{ (say)}$$

Here the first term gives the normal displacement and the second the anomalous or "viscous" displacement (D_v). The final displacement is given by

$$D_\infty = \frac{\epsilon E_0}{4\pi v^2}(1 + \gamma)$$

Now

$$\frac{dD_t}{dt} = \alpha e^{-\alpha t}\gamma\frac{\epsilon E_0}{4\pi v^2} = \alpha(D_\infty - D_t)$$

When the field strength varies with time we have

$$\frac{d}{dt}D_t = \frac{\epsilon}{4\pi v^2} \times \frac{dE}{dt} + \frac{dD_v}{dt}$$

where the second term is subject to

$$\begin{aligned} \frac{d}{dt}D_v &= \alpha(D_\infty - D_t)\dagger \\ &= \alpha\left[\frac{\epsilon}{4\pi v^2} \times E_t(1 + \gamma) - D_t\right] \\ &= \alpha\left[\gamma\frac{\epsilon}{4\pi v^2}E_t - D_v\right] \\ \therefore \frac{d}{dt}D_v + \alpha D_v &= \alpha\frac{\epsilon}{4\pi v^2}\gamma E_t \end{aligned}$$

This equation may also be obtained thus,

$$D_v = \epsilon\frac{E_t}{4\pi v^2}(1 - e^{-\alpha t})\gamma \quad . \quad . \quad . \quad \text{(A)}$$

Differentiating,

$$\frac{dD_v}{dt} = \epsilon\frac{E_t\gamma\alpha e^{-\alpha t}}{4\pi v^2}$$

Substituting from above (A) for $e^{-\alpha t}$

$$\frac{dD_v}{dt} = \frac{\alpha\epsilon E_t\gamma}{4\pi v^2} = \alpha D_v$$

$$\text{i.e.} \quad \frac{dD_v}{dt} + \alpha D_v = \frac{\alpha\epsilon E_t\gamma}{4\pi v^2}$$

* STEINMETZ, *loc. cit.*
† THORNTON: *Proc. Phys. Soc.*, 1910, vol. 22, p. 186.
‡ S. W. RICHARDSON: *Proc. Roy. Soc.*, 1916, vol. 92, p. 41.
§ H. A. WILSON: *Proc. Roy. Soc.*, 1909, vol. 82, p. 409.
|| F. W. GROVER: *Bulletin Bureau of Standards* 1911 vol. 7, p. 519.

* PELLAT: *Ann. Chimie et Phys.*, 1899, vol. 18, p. 150.
† D_∞ here being the final value corresponding to the instantaneous value E_t.

This is the general equation giving the viscous displacement in terms of the field strength. Take the special cases

1. Constant voltage E_0 applied at instant $t = 0$. Then

$$D = \frac{\epsilon}{4\pi v^2}E_0 + (1 - e^{-at})\gamma\frac{\epsilon E_0}{4\pi v^2}$$

$\therefore$ Displacement current density $= \dfrac{dD}{dt}$

$$= \frac{\epsilon E_0}{4\pi v^2}a\gamma e^{-at}$$

Thus for a condenser we have for the anomalous current

$$i_2(t) = E_0 C a\gamma e^{-at}$$

This is exactly the same as the formula given by Maxwell's theory. The only difference is that Maxwell's

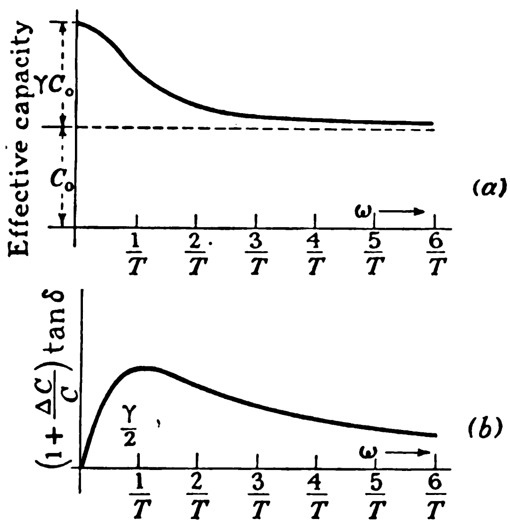

FIG. 23.—Variation of effective capacity and power loss per cycle with frequency (Pellat's theory).

theory expressed the constants in terms of the physical constants of the components of the dielectric. As in the previous case, this current obeys the Superposition Law.

2. With sine-wave voltage $E = E_0 \sin \omega t$, we find that the apparent increase of capacity due to absorption is given by

$$\frac{\Delta C}{C} = \frac{\gamma}{1 + \omega^2 T^2} \text{ putting } a = \frac{1}{T}$$

and the loss angle by

$$\frac{C + \Delta C}{C}\tan\delta = \frac{\gamma\omega T}{1 + \omega^2 T^2}$$

C is the value of the capacity when there is no absorption. It is called the geometric capacity of the condenser.

According to these formulæ the change of capacity with frequency should be as in Fig. 23 (*a*) and $\tan\delta$ should vary with frequency as indicated in Fig. 23 (*b*). Thus the power loss per cycle will be zero at zero frequency. As the frequency is increased the power loss per cycle first increases rapidly, reaching a maximum at the frequency defined by

$$\omega = \frac{1}{T}$$

It then decreases, at first rapidly and then more and more slowly, approaching the zero value again at very high frequencies. The effective capacity should increase as the frequency diminishes, reaching a maximum $C_0(1 + \gamma)$ at zero frequency.

(*c*) *Schweidler's theory.**

As was pointed out in the case of Maxwell's theory, these simple relations do not explain the observed facts. The characteristic time function $f(t)$ of the absorption current is not a simple exponential function, and the variations of capacity and $\tan\delta$ with frequency are not in general as indicated by these curves. In the case of Maxwell's theory it has been shown that the assumption of a number of components in the dielectrics leads to an expression for $f(t)$ consisting of the sum of a number of exponential terms. Schweidler similarly extended Pellat's theory by writing

$$D = \frac{\epsilon}{4\pi v^2}E_0 + \Sigma D_n'$$

where $\Sigma D_n'$ represents the sum of a number of "viscosity" terms each of which is subject to the relation

$$\frac{d}{dt}D_n' = a_n\left[\gamma_n\frac{\epsilon}{4\pi v^2}E - D_n'\right]$$

For the case of a constant voltage applied at $t = 0$ we then obtain

$$D = \frac{\epsilon}{4\pi v^2}E_0 + \frac{\epsilon}{4\pi v^2}E_0\Sigma\gamma_n(1 - e^{-a_n t})$$

and for the anomalous current

$$i_2(t) = E_0 C\Sigma a_n\gamma_n e^{-a_n t}$$

Thus again $f(t)$ is represented by a series of exponential terms.

Schweidler further supposed that there are an infinite number of such terms, the constants a_n varying continuously from 0 to ∞. The quantities γ_n will be function of a, say $\gamma(a)$, we then have

$$D_\infty = \frac{\epsilon}{4\pi v^2}E_0\left[1 + \int_0^\infty \gamma(a)da\right]$$

$$D_t = \frac{\epsilon}{4\pi v^2}E_0\left[1 + \int_0^\infty \gamma(a)\{1 - e^{-at}\}da\right]$$

$$i_2(t) = E_0 C\int_0^\infty a\cdot\gamma(a)\cdot e^{-at}da$$

and with impressed voltage $V = V_0 \sin \omega t$.

$$\frac{\Delta C}{C} = \int_0^\infty \frac{\gamma(a)a^2}{\omega^2 + a^2}da$$

$$\left\{\frac{C + \Delta C}{C}\right\}\tan\delta = \int_0^\infty \frac{\gamma(a)\omega a}{\omega^2 + a^2}da$$

* SCHWEIDLER: *Ann. der Physik*, 1907, vol. 24, p. 742.

The function $\gamma(\alpha)$ could be determined from any set of experimental results. On this theory in order to specify completely the behaviour of a dielectric we must know the dielectric constant ϵ, the specific resistance ρ and the function $\gamma(\alpha)$. Like Maxwell's theory it is obviously capable of explaining almost any set of experimental results by a suitable choice of $\gamma(\alpha)$, but as this function is the equivalent of a large number of constants it is not of great practical value.

Schweidler has given a molecular interpretation of his extension of Pellat's theory. A dielectric is regarded as possessing ions or electrons which when displaced from their position of equilibrium vibrate about that position with definite natural periods of vibration. In addition to molecules whose ions possess a definite natural period and definite damping, Schweidler supposes others to be present in which the damping is so great that their motion is aperiodic. Under the influence of a constant field suddenly applied, these ions approach a new equilibrium position in such a way that their deviation from it diminishes the exponential function $e^{-\alpha t}$. The ions with a definite natural period (very small) provide the normal displacement, while the aperiodic ions provide the " viscous " displacement.

$$T = \frac{1}{\alpha}$$

is the time-constant of these aperiodic ions and γ is the ratio of the displacement due to aperiodic ions to that due to ions whose motion is oscillatory. Pellat's theory implies only one kind of these aperiodic ions all with the same time constant. Schweidler's extension assumes a large number of different kinds of ions having different time constants, γ_n is proportional to the number per unit volume having the constant α_n. The next stage regards the damping as varying continuously, and the function $\gamma(\alpha)$ shows according to what law these ions are distributed as α varies continuously between 0 and ∞.

On Maxwell's theory, each additional exponential term means another constituent in the composition of the dielectric. If the constituents can be regarded as mixing in varying proportions in different parts of the dielectric, we shall obviously get a series of exponential terms in which α may vary continuously. Thus, whatever can be explained by Schweidler's theory can also be explained by Maxwell's.

(*d*) *Wagner's * distribution law for the time-constants.*

The general expression for the electric displacement on Pellat's theory is

$$D = \frac{\epsilon E}{4\pi v^2} + \int_{-\infty}^{t} \frac{\epsilon E}{4\pi v^2} \frac{d}{du}\left[\gamma e^{-\frac{t-u}{T}}\right] du$$

where E, the electric field, is a function of time,

u is the integration variable,

$T = 1/\alpha$ is the time-constant.

* K. W. WAGNER: *Ann. der Physik*, 1913, vol. 40 p. 817.

Schweidler's extension of the theory to the case in which there are a series of terms of different time-constants may be expressed

$$D = \frac{\epsilon E}{4\pi v^2} + \int_{-\infty}^{t} \frac{\epsilon E}{4\pi v^2} \frac{d}{du}[\psi(t-u)]du$$

where $$\psi(t) = \sum_n \gamma_n e^{-\frac{t}{T_n}}$$

In the case in which the number of terms is made infinite the variable

$$T_n\left(=\frac{1}{\alpha_n}\right)$$

varying continuously, we have

$$\psi(t) = \int_0^{\infty} \gamma(T) dT e^{-\frac{t}{T}}$$

Here $\gamma(T)\,dT$ is the amplitude sum of all the terms of

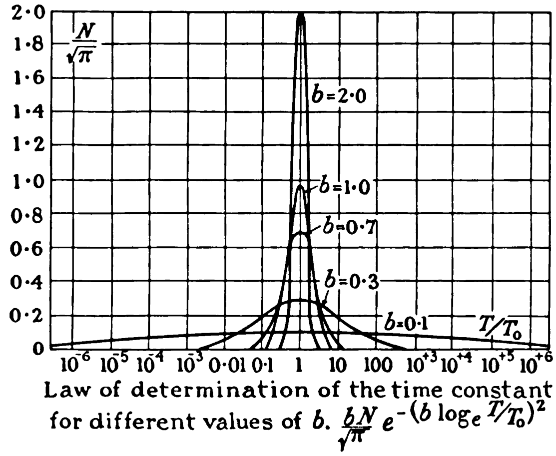

FIG. 24.—Law of distribution of the time-constants.

time-constant in the range T to $T + dT$. Thus we may regard $\psi(t)$ as the law of distribution of the time-constants. Wagner has proposed for this distribution law

$$\gamma(T)dT = \frac{\gamma b}{\sqrt{\pi}} e^{-b^2 z^2} dz, \text{ where } z = \log_e \frac{T}{T_0}$$

This law was first given by Wiechert * in explanation of the phenomena of elastic after-effect in solids. It means that there is a certain time-constant T_0 which is the most prominent, and the logs of the time-constants of the various terms are grouped about $\log T_0$, the greater the constant b the more dense is the grouping. This is illustrated by Fig. 24.

Wagner found

$$\psi(t) = \frac{\gamma b}{\sqrt{\pi}} \int_{-\infty}^{+\infty} e^{-b^2 z^2 - \frac{t}{T_0} e^{-z}} dz$$

$$\psi(o) = \gamma$$

* E. WIECHERT: *Wied. Ann.*, 1893, vol. 50, p. 335.

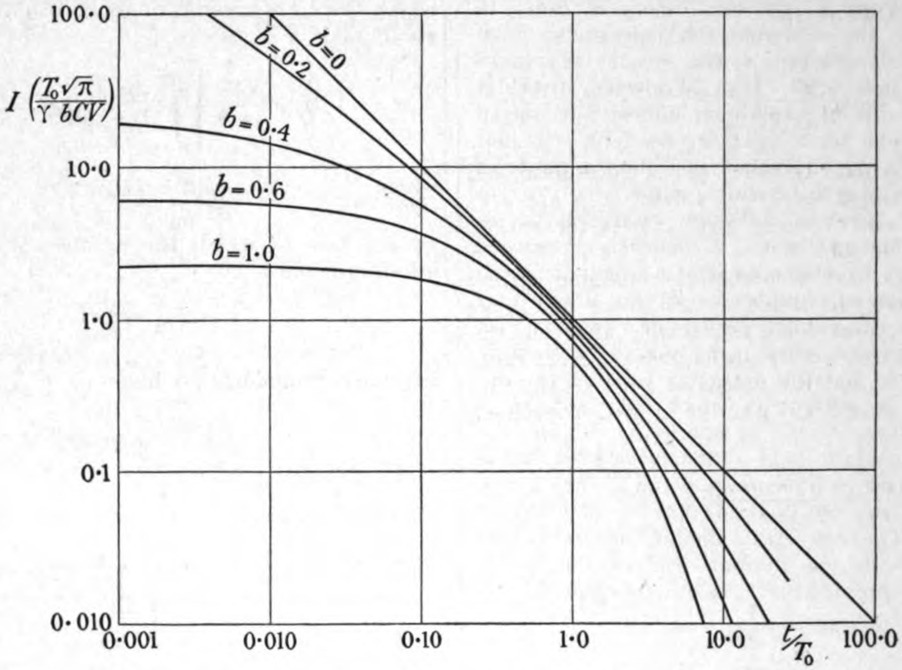

FIG. 25.—Anomalous current function in terms of time constant and b.

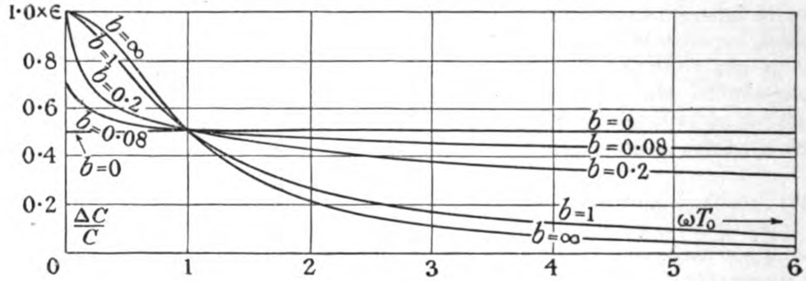

FIG. 26.—Capacity increment as a function of ωT_0 (Wagner).

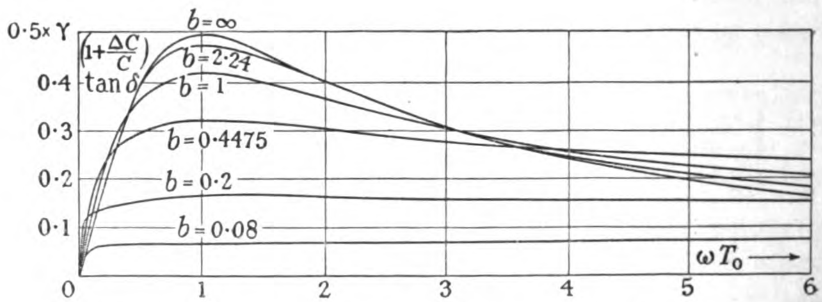

FIG. 27.—Power loss per cycle as a function of ωT_0 (Wagner).

In the case of constant voltage E_0 suddenly applied at the instant $t = 0$, we obtain

$$i_2(t) = E_0 C_0 \frac{\gamma b}{T_0\sqrt{\pi}} \int_{-\infty}^{+\infty} e^{-b^2z^2 - z - \frac{t}{T_0}e^{-z}} dz.$$

This cannot in general be evaluated in finite form, but it can be determined for given values of b and t/T_0 by Simpson's rule. Wagner gives curves for various values of b (see Fig. 25).

In practice we have seen that the charging current decreases at first very rapidly, then more and more slowly, in some cases being appreciable after months. Thus it is concluded we are dealing with a great range of time-constants, and the values of b are small. For these small values of b it is possible to make convenient approximations *:—

(1) $$-\frac{d\psi}{dt} = \frac{\gamma b}{T_0\sqrt{\pi}} \frac{T_0}{t} e^{-\left(b \log \frac{t}{T}\right)^2}$$

from which

$$\log_{10} i_2 = \text{constant} - \log_{10} \frac{t}{T_0} - \frac{b^2\left(\log_{10} \frac{t}{T}\right)^2}{\log_{10} e}$$

When log i_2 is plotted against log t this is represented by a parabola, which at the point $t = T_0$ has its tangent sloping at $-45°$ to the log t axis.

(2) Over a limited time range, we can express

$$\frac{d\psi}{dt}$$

and therefore i_2 by

$$i_2 = Bt^{-m}$$

where $$m = 1 + 2b^2 \log_e \frac{T}{T_0}$$

T being the value of t in the middle of the range of time considered. This is the experimental law given by most observers. It obviously holds over such a range that the parabola mentioned above may be considered as a straight line. In practice m is usually found to be less than unity. The above formula seems to indicate that it may also be >1. In no case does this seem to have been found. Schweidler pointed out that there are two difficulties associated with the formula

$$i_2(t) = Bt^{-m}, \text{ viz. } i_2(0) = \infty \quad \text{and} \quad \int_0^\infty i_2(t)dt = \infty$$

both of which are highly improbable. If, however, we take the full formula given by Wagner we get

$$i_2(0) = CE_0 \frac{\gamma}{T_0} e^{\frac{1}{4b^2}}$$

$$\int_0^\infty i_2(t)dt = CE_0\psi(0) = CE_0\gamma$$

both of which are finite.

* K. W. Wagner: *Ann. der Physik*, 1913, vol. 40, p. 833.

Consider now the case of sine-wave applied voltage. Wagner obtains

$$\frac{\Delta C}{C} = \frac{\gamma b}{\sqrt{\pi}} \int_0^\infty \frac{dt}{T} \cdot \frac{1}{1 + \omega^2 T^2} e^{-\left(b \log_e \frac{T}{T_0}\right)^2}$$

and putting $z = \log_e \dfrac{T}{T_0}$

$$z_0 = \log_e \omega T_0$$

$$z + z_0 = u$$

$$\frac{\Delta C}{C} = \frac{\gamma b}{\sqrt{\pi}} e^{-b^2 z_0^2} \int_0^\infty e^{-b^2u^2} \cdot \frac{\cos (2b^2 z_0 - 1)u}{\cos u} \cdot du$$

$$\left(1 + \frac{\Delta C}{C}\right) \tan \delta = \frac{\gamma b}{\sqrt{\pi}} e^{-b^2 z_0^2} \int_0^\infty e^{-b^2u^2} \cdot \frac{\cos 2b^2 z_0 u}{\cos u}$$

Tables and curves illustrating these formulæ are given in Wagner's paper.* The most important consequences of the formulæ are

1. At zero frequency $\Delta C/C = \gamma$ for all values of b.
2. At the frequency given by $\omega = 1/T_0$, $\Delta C/C = \frac{1}{2}\gamma$ for all values of b.
3. When b is vanishingly small, $\Delta C/C$ takes the constant value $\frac{1}{2}\gamma$, i.e. the capacity becomes independent of the frequency.
4. $1 + \Delta C/C \tan \delta$ (which gives the power loss per cycle when the voltage is unity) is zero when the frequency is zero: as the frequency increases it rises to a maximum at the point $\omega = 1/T_0$ and then decreases, finally approaching zero value at very high frequencies.
5. For very small values of b, $\tan \delta$ tends to become constant like ΔC.

These deductions are illustrated by Figs. 26 and 27.

(*e*) *Wagner's extension of Maxwell's theory.*

Wagner first published the above considerations by way of continuation of Schweidler's work on Pellat's theory. In a subsequent paper † he has shown how the formulæ can also be derived from Maxwell's theory. It is obvious that this must be so since the two theories lead to identical equations. Wagner describes a model dielectric structure, and develops the equations of the after-effect which it will show. The basic substance of the structure is considered to be a perfect dielectric of dielectric constant ϵ. Distributed throughout its mass are a number of small spheres of dielectric constant ϵ and conductivity σ. The dielectric is to be imagined as filling a plate condenser. In the absence of the spheres the field would be uniform. Each sphere causes a distortion of the field which is of most importance inside it, and in its immediate neighbourhood, but becomes negligible at great distances. It is now assumed that the spheres are so far apart that each disturbs

* K. W. Wagner: *Ann. der Physik*, 1913, vol. 40, p. 833.
† K. W. Wagner: *Arch. für Elektr.*, 1914, vol. 2, p. 371.

the field only just as much as if the others were absent. The behaviour of the dielectric under the uniform alternating field $E_0 e^{j\omega t}$ is then considered. The expression obtained for the electric displacement is

$$D = \frac{\epsilon E}{4\pi v^2}\left[1 + \frac{3p}{1 + \omega^2 T^2} - j\frac{3p\omega T}{1 + \omega^2 T^2}\right]$$

where $T = \dfrac{3\epsilon}{4\pi v^2 \sigma}$

$p =$ the ratio of the volume occupied by the small spheres to that of the basic substance.

This equation is seen to be of exactly the same form as given by Maxwell's theory of the simple laminated dielectric and Pellat's theory. It is pointed out that the constant, T, depends only on the material and not on the size of the spheres. Wagner then supposes that there are n different sorts of spheres all with different conductivity $\sigma_1, \sigma_2 \ldots \sigma_n$, and that their relative volume densities are $p_1 \ldots p_n$. If they are still sufficiently far apart not to affect each other we get

$$D = \frac{\epsilon E}{4\pi v^2}\left[1 + \sum_n \frac{3p_n}{1 + \omega^2 T_n^2} - j\sum_n \frac{3p_n \omega T_n}{1 + \omega^2 T_n^2}\right]$$

This equation of course leads to the various others which have been given.

A possible explanation of the distribution law of the time-constants is then given as follows: the time-constant T_n depends on the conductivity of the small particles and not on their size. Assume now that the different values of conductivity σ_n are not due to different substances, but to the same conducting substance mixed in different proportions with the basic substance. Thus p_n is a measure of the number of particles in which the mixture is of a certain definite proportion. Suppose, now, that the conducting substance tends to form small spheres of uniform composition corresponding to a time-constant T_0. A number of disturbing factors may tend to upset this uniformity both in the direction of increasing and of decreasing conductivity. Assume that any one of these disturbing causes, independently of all the others, tends to alter the composition of any sphere in the ratio $(1 + q)$. The change is as likely to be in one direction as in the other. Since the time-constant is inversely proportional to the quantity of conducting material, the disturbing factor changes the time-constant in the ratio $(1 + q)^{\pm 1}$. Denoting the effect of the different disturbing causes by successive indices, then the final value of the time-constant of any sphere may be written

$$T_r = T_0(1 + q_1)^{\pm 1}(1 + q_2)^{\pm 1}(1 + q_3)^{\pm 1} \ldots$$

$$\therefore \log T_r = \log T_0 \pm \log(1 + q_1) \pm \log(1 + q_2) \ldots$$

Put $\log T_r = z_r$, etc., and $\log(1 + q_1) = \delta_1$, etc.

$$\therefore z_r = z_0 \pm \delta_1 \pm \delta_2 \pm \delta_3 \ldots$$

If there are a great many terms δ and if they are as likely to be $+$ as $-$, then it follows from the laws of probability that the magnitudes z_r are grouped about the value z_0 according to the law: the number between z_r and $z_r + dz$ is proportional to

$$e^{-b^2(z_r - z_0)^2} dz.$$

The constant b measures the density of distribution of the magnitude z_r around z_0. Its value depends on the strength of the disturbing factors.

Thus the number of small spherical particles with time-constants between

$$T_r \text{ and } T_r\left(1 + d\log\frac{T_r}{T_0}\right)$$

is proportional to

$$e^{-\left(b\log\frac{T_r}{T_0}\right)^2} d\left(\log\frac{T_r}{T_0}\right).$$

Now the number of spheres with time-constant T_n is proportional to p_n, the volume ratio. Also $3p_n$ corresponds to γ_n. Hence

$$\sum_{T_r}^{T_r\left(1 + d\log\frac{T_r}{T_0}\right)} 3p_r = \gamma(T_r)dT_r = Be^{-\left(b\log\frac{T_r}{T_0}\right)^2} d\log\frac{T_r}{T_0}.$$

The proportionality factor B is determined by the fact that the sum of all the values $\gamma(T_r)$ is equal to γ in

$$D_\infty = \frac{\epsilon E}{4\pi v^2}(1 + \gamma) \text{ i.e.}$$

$$\int_0^\infty \gamma(T_r)dT_r = \gamma$$

which gives $B = \gamma b/\sqrt{\pi}$.

Thus the distribution law we arrive at is that previously given, viz. :—

$$\gamma(T)dT = \frac{\gamma b}{\sqrt{\pi}} e^{-b^2 z^2} dz, \text{where } z = \log\frac{T}{T_0}$$

Thus all the deductions made in Section III of this chapter apply to this dielectric model.

The theory is then extended by supposing that instead of a single conducting substance there are several, each of which tends to form spheres of a certain composition, but is influenced by disturbing factors. Thus there will be a number of characteristic time-constants

$$T_{0m} = \frac{3\epsilon}{4\pi v^2 \sigma_m}$$

There will also be a number of factors b_m governing the density of distribution of the time-constants around these values. Each of these characteristic time-constants may be expected to give rise to a maximum on the curve connecting power loss and frequency. In fact this curve may be regarded as a kind of spectrum, on which the peaks correspond to time-constants characteristic of the material.

The spherical form assumed for the conducting particles is not essential to the theory. In the formulæ it is only the disturbance of the electric field at great distances from the particles which is used, and this does not depend on the form of the particle.

(*f*) *Thornton's theory of "Inter-attraction."*

In his various papers,* Thornton has sketched a theory of the "absorption" phenomena without assuming the existence of any "abnormal" ions or inhomogeneities in the structure. The "viscous" displacement is regarded as an additional displacement of the electrons, whose initial displacement constitutes the normal charge, and this additional displacement is attributed to the forces of attraction between the displaced electrons of adjacent molecules. The theory is not mathematically developed, and it is somewhat difficult to see how it can be made to explain the observed facts. Such attraction must, of course, occur, and undoubtedly plays a part in determining the normal displacement, but there seems to be nothing to explain why this "secondary" displacement should be very slow, as it must be if it accounts for "absorption." Similarly it is not obvious why this secondary displacement should lead to power loss in alternating fields, since it is essentially of the same nature as the normal displacement, i.e. a movement of the same electrons, and the normal displacement is always regarded as being free from power loss. The theory can hardly be regarded as well established, as unlike the preceding theories it has not yet been shown to be capable of explaining the observed facts, such as the Superposition Principle.

One experiment of Thornton's, made to determine the nature of the slow polarization, is of particular interest. A flint-glass ellipsoid was suspended in a glass cell, the upper part having pole plates so that an electrostatic field could be maintained there, and the lower being filled with carbon disulphide. The ellipsoid was exposed to the action of the electrostatic field for several days, until it had reached the final stage of polarization. Its time of swing was then noted, this giving a measure of the polarization. It was then lowered into the liquid and exposed to the action of radiation from a tube of radium bromide. After five minutes' exposure the ellipsoid was raised and allowed to stand in the field for the same time that it had been removed from it; its period was found to be unchanged. The object of the liquid was to shield the ellipsoid from the effects of ions in the surrounding space. Thornton concludes:—

"If the charge on the ellipsoid had been in any sense free, whether residing on the surface or inside, it would have been rapidly removed and the period lengthened by exposure to the radium. . . . It would appear from this that the electrical movement in a dielectric when isolated in the field is entirely confined to the molecule and is therefore neither metallic nor electrolytic in type, but is the continued displacement of the atomic charges to a greater degree of separation than has been hitherto recognized." †

This point is, of course, of the greatest importance. If it is sound, it rules out the possibility of Maxwell's theory applying in the case considered, since on this theory charges do accumulate inside the dielectric at the surface of separation of the various components. It would not necessarily rule out Schweidler's theory. The general trend of Thornton's work is to make it seem very doubtful whether Maxwell's theory is capable of explaining all the anomalous phenomena shown by dielectrics.

(*g*) *Ionic theories.*

It has been mentioned in a previous section that certain phenomena shown by dielectrics, particularly the non-reversible anomalous current characteristic of liquids, suggest that in certain cases at least electricity is transported through the dielectric by means of ions as in electrolysis. Various attempts have been made to explain the different anomalies in this way. Schweidler, in Graetz's "Handbuch der Elektrizitat und des Magnetismus," gives a summary of the earlier work. In recent years comparatively little reference has been made to this theory in connection with the power losses in dielectrics, but in considering the phenomena of breakdown, Günther-Schulze * has made considerable use of it. He considers that breakdown in liquids occurs in the following manner. The heat generated by the motion of the ions against frictional forces creates bubbles of vapour, in which breakdown takes place as a consequence of ionization by collision, i.e. the breakdown of liquids is essentially a masked gas discharge. He considers that solid insulators should be divided into two classes

1. *True dielectrics.*—These are approximate non-conductors in the melted state and contain only an extremely small number of ions, if any. Examples are sulphur, paraffin wax.

2. *Pseudo dielectrics.*—These are bodies, which in the liquid state are comparatively good conductors, and are almost completely dissociated into ions. On cooling their conductivity decreases enormously, but it is considered that this is due not to a change in the number of ions so much as to a change in their mobilities, which are fairly large near the melting-point, but decrease with temperature very rapidly according to a logarithmic law. Such bodies are really conductors. They only behave as dielectrics at temperatures far removed from their melting-points on account of the great frictional resistance to the motion of the ions. Examples given of this class are glass, porcelain, marble, mica and all solid salts.

The mechanism of breakdown is thought to be different in different cases. In some cases the electric strength is determined by the field strength necessary to cause the ions already present to generate other ions by collision. In other cases the strength is determined by the field-strength necessary to increase the displacement of the atomic charges until the restoring force is overcome.

The same writer applies the idea of ionization by collision in solid dielectrics in order to explain results obtained by H. H. Poole † for the conductivity of glass at high field strengths. Poole gives the formula

$$\log \sigma = a + bD$$

or

$$\sigma = e^{a+bD}$$

* W. M. THORNTON: *Proc. Phys. Soc.*, 1910, vol. 22, p. 186. *Electrician*, 1913, vol. 71, p. 214. *Phil. Mag.*, 1913, vol. 30, p. 124. *Phil. Mag.*, 1915, vol. 30, p. 124. *Proc. Phys. Soc.*, 1912, vol. 24, p. 311.

† The exact effect of the radiations is so doubtful that one would require more evidence before accepting any deductions made on the assumption of a specific effect.

* GUNTHER-SCHULZE: *Zeits. für Instr.*, March 1923 p. 72.

† H. H. POOLE: *Phil. Mag.*, 1921, vol. 42, p. 488.

where σ = conductivity
D = field strength
e^a = is the electrolytic conductivity at low voltage.

Günther-Schulze * shows that this formula can be deduced by assuming that at high field strengths an ion may generate other ions by collision, the number so generated per unit length of its path being proportional to the field strength E. Further work is necessary before the theory can be regarded as established, but it is of considerable interest.

(*h*) *Debye's dipole theory.*

Debye's dipole theory is another theory of great interest in connection with the anomalies in the behaviour of dielectrics. It does not yet appear to have been considered in connection with power losses and "absorption phenomena" generally, but it seems probable that it would have considerable bearing on these matters. Debye † approaches the subject from the point of view of the physical chemist, and sets out to explain the large temperature coefficient of the dielectric constant of certain liquids such as the alcohols. He points out that the modern idea of the structure of a dielectric is that it consists of molecules in which there are electrons which cannot easily escape from the molecule, but which can be displaced a certain distance against a restoring force which binds the electron to the molecule and which is proportional to the displacement. The consequences of this theory as regards dispersion and the Zeeman effect are indisputable,‡ but it fails to explain the large temperature coefficient mentioned above. Debye therefore assumes that the molecules of a dielectric may contain, in addition to the elastically bound electrons (the displacement electrons), complete electric dipoles of constant moment. These are the electrical equivalent of molecular magnets, and the behaviour of such a body in an electric field is obviously analogous to that of a magnetic substance in a magnetic field; in fact, Langevin's theory of paramagnetism is applied. Thus when the dielectric is placed in an electric field, the displacement produced consists of two parts: (1) that due to the displacement electrons, and (2) that due to electric dipoles turning more or less into alignment with the field. The first part depends very little on temperature, but the second varies greatly with temperature changes. Debye develops a formula which accounts for many of the observed facts. It is

$$\frac{\epsilon - 1}{\epsilon - 2} = \frac{a}{T} + b$$

where ϵ is dielectric constant,
T is absolute temperature,
a and b are constants.

The inference is that certain liquids do contain such dipoles. The question then arises, Is this second term in the electric displacement elastic like the first, or does it give rise to power loss in alternating fields? Is there a true hysteresis effect? Nothing appears to have been published on this point.

Another interesting development of this theory is that the displacement no longer becomes exactly proportional to the applied field, i.e. at high intensities there is an apparent decrease in the dielectric constant.*

These questions are as yet of more interest from the point of view of molecular structure than of electrotechnics, and all the work appears to have been done by physical chemists who ignored power losses and absorption effects. Their results are, however, very suggestive.

* GÜNTHER-SCHULZE: *Phys. Zeitschrift*, 1923, vol. 24, p. 212.
† DEBYE: *Phys. Zeitschrift*, 1912, vol. 23, p. 97.
‡ This statement requires some qualification. Modern work has largely discredited the application of the classical electron theory to many dispersion phenomena and to the Zeeman effect.

V. The Experimental Laws of the Power Losses in Dielectrics.

In the present section the actual experimental results obtained for the power losses in various commercial dielectrics will be considered. The values will be examined in the light of the theories mentioned in the previous section, with a view to determining, if possible, the cause of the power loss. It is convenient to consider in turn the variation of power loss with

1. Frequency.
2. Temperature.
3. Change of state.
4. Voltage.
5. Moisture content.

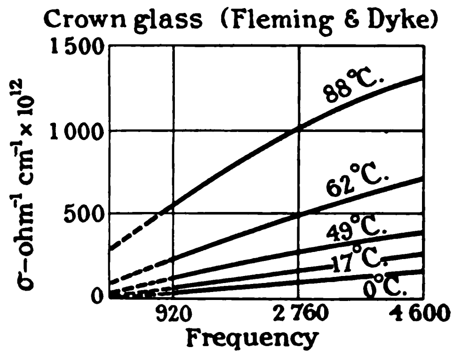

FIG. 28.—Variation of a.c. conductivity with frequency for crown glass.

(*a*) *The variation of power loss with frequency.*

(i) *Solid dielectrics.*—The earliest systematic investigation of this matter is that of Fleming and Dyke.† They investigated a number of materials including glass, ebonite, paper, gutta-percha, rubber, all in the form of thin sheets. Tin-foil electrodes were used, and each material was examined at three frequencies, all in the telephonic range, viz. 920, 2 760 and 4 600~. The power loss was expressed by giving the "alternating current conductivity" (σ) of the material. As was shown in Section I, the product of σ and the square of the effective voltage gives the power loss per cm³. Fig. 28 shows the results given by Fleming and Dyke for crown glass. These curves are typical of the results

* RATNOWSKY: *Verh. Deutsch. Phys. Gesell.*, 1913, vol. 15, p. 497.
† FLEMING and DYKE: *Journal I.E.E.*, 1912, vol. 49, p. 323.

found for practically all the dielectrics examined. The authors interpret the results as follows :—

The curves are regarded as approximating to straight lines, i.e. the effective conductivity of the material (or the power loss) is a linear function of the frequency, and we may write

$$\sigma = a + bf$$

The constant a is the conductivity at zero frequency, and is considered as representing the direct-current conductivity. b is considered to represent a constant hysteresis loss per cycle. As a possible explanation of this hysteresis loss, it is suggested that with increasing displacement, the electrons or ions are brought into an unstable position, from which they fall freely into a new position of equilibrium, and dissipate the energy expended in displacing them, in the form of electromagnetic waves, due to rapid free oscillations about the new position of equilibrium.

It is to be noted that each of these curves is derived from three points only, so that it is by no means certain that their course is that indicated by the authors. Further, the lines show distinct curvature, so that at the best this linear law can only be regarded as a rough approximation. It has been mentioned that the constant a should represent the direct-current conductivity.

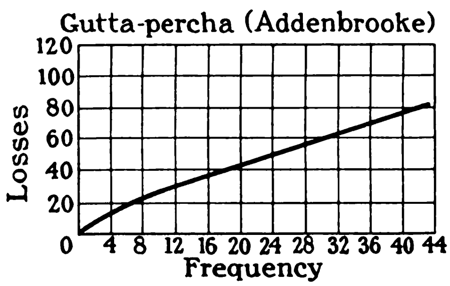

FIG. 29.—Variation of loss with frequency for gutta-percha.

Now a for crown glass at 17° C. is given as $8 \cdot 6 \times 10^{-12}$ ohm^{-1}, cm^{-1} which corresponds to a resistivity of about $1 \cdot 2 \times 10^{-1}$ ohm cm, whereas the generally accepted value is of the order 10^{-13}, i.e. a hundred times as great. Thus it is very doubtful whether the interpretation of the results given is correct. Further observations at different frequencies are necessary before any definite conclusions can be drawn, in particular observations at lower frequencies, and observations on the same specimen with direct current.

A certain number of observations at very low frequencies have been given by Addenbrooke,* together with the corresponding d.c. observations. Addenbrooke found that

1. The losses are approximately a linear function of the frequency, and this approximation becomes closer as the frequency becomes higher.
2. As the frequency gets lower the straight line bends over more towards the axis of frequency.
3. The direct-current value is considerably lower than the value at frequencies as low as $0 \cdot 2$ cycle per second.

* ADDENBROOKE : *Electrician*, 1913, vol. 70, p. 673.

Thus the general form of the curve given by Addenbrooke is as shown in Fig. 29. The observations were made chiefly on celluloid and gutta-percha in the form of thin sheets. Mercury electrodes were used, and frequencies of 1/5 to 50 cycles per second.

Proceeding now to higher frequencies an important series of observations has been made by Bairsto.* He used more or less the same materials as Fleming and Dyke, and made up condensers with tin-foil electrodes in the same way. Observations were made over a considerable range of radio frequencies. A typical set of Bairsto's results—those for crown glass—are shown in Fig. 30. The results are seen to be greatly different from those at lower frequencies. The law $\sigma = a + bf$ is no longer even roughly obeyed. As the frequency increases, the conductivity rises at first slowly, afterwards more rapidly. It then reaches a maximum, after which it decreases with an increase in frequency.

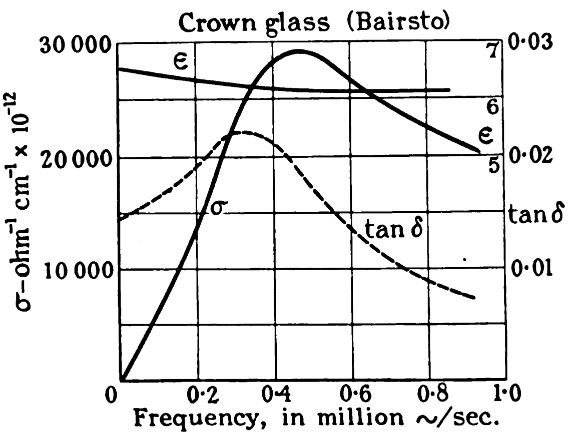

FIG. 30.—Variation of a.c. conductivity, permittivity and power factor of crown glass with frequency.

The values of the conductivity at the radio frequencies are very much greater than they are at telephonic frequency.

As regards the interpretation of the results, Bairsto follows the line of thought started by Fleming and Dyke. At telephonic frequencies he regards the losses as consisting of two parts, a the d.c. loss, $+ bf$ the true hysteresis loss. He points out that as the frequency increases, σ soon begins to increase more rapidly than the law $\sigma = a + bf$ indicates. He accordingly writes $\sigma = a + bf + cf^2$. The additional term cf^2 is considered to represent loss due to dielectric viscosity. This is considered to be negligible at telephone frequency, but to become the predominant component at radio frequencies. The power loss per cycle is very nearly represented by $\tan \delta$. Bairsto points out that at telephonic frequencies $\tan \delta$ is approximately constant, being determined mainly by the constant loss per cycle, b. As the frequency is increased into the radio range, $\tan \delta$ increases on account of the viscosity loss cf^2. Eventually $\tan \delta$, like σ, reaches a maximum value, and then begins to decrease. This decrease

* BAIRSTO : *Proc. Roy. Soc.* 1920, vol. 96, p. 363.

continues until the value becomes even less than that at telephonic frequencies. Bairsto accounts for this by supposing that the hysteresis loss per cycle b, though constant at telephonic and lower frequencies, decreases as the frequency is raised, and becomes very small at the higher radio frequencies, so that at these frequencies only the viscous loss is of any importance.

The results found by Bairsto for various other dielectrics were very similar in general character to those for crown glass. In all cases σ reached a maximum value and then decreased. In some cases there were subsidiary maxima, which were interpreted as due to some particular component of the dielectric.

The interpretation of their results by these various authors was made without any particular reference to the theories of absorption or after-effect. Now it is

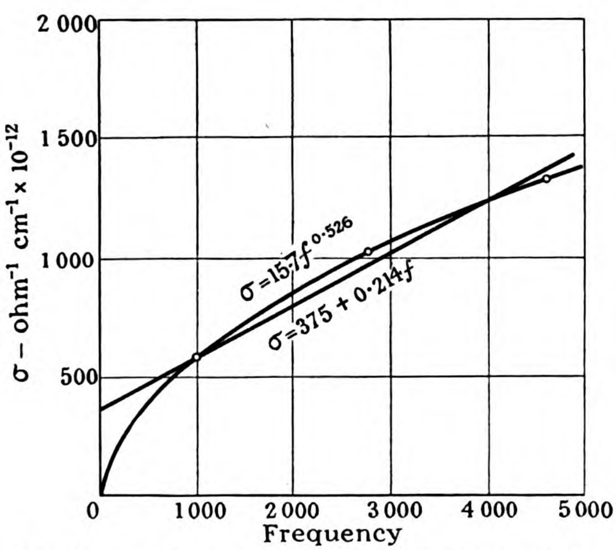

FIG. 31.—Variation of a.c. conductivity with frequency.

fairly certain that a considerable part of the loss is due to this cause, and an examination of the results in the light of the theories yield some very interesting facts.

In the first place, Bairsto's results show that when observations are made over a very great range of frequencies, no very simple law of power is to be expected.

The linear law of Fleming and Dyke can only hold over a range of frequency so small that the element of the conductivity curve contained by it can be considered a straight line. The equation $\sigma = a + bf$ probably merely represents the tangent of the conductivity curve at the point considered, and has no particular physical meaning.

We have seen that Schweidler's theory (Section II, p. 1164) indicates that the power loss due to absorption should be given by

$$W = E^2 A\omega^m$$

or $$\sigma \doteq A\omega^m \text{ where } o < m < 1$$

or $$\sigma = Gf^m \text{ where } f = \text{frequency} = \frac{\omega}{2\pi}$$

Some of Fleming and Dyke's results were examined in order to see how they fitted in with this equation. Taking the results for crown glass, they were found to obey the law probably within the experimental error, and certainly much better than they did the law $\sigma = a + bf$. The equations found were as follows :—

Crown Glass.

Temperature	Equation $\sigma = Gf^m$
0° C.	$\sigma = 0{\cdot}073f^{0\cdot91}$
17° C.	$\sigma = 0{\cdot}136f^{0\cdot889}$
49° C.	$\sigma = 0{\cdot}557f^{0\cdot78}$
62° C.	$\sigma = 2{\cdot}26f^{0\cdot68}$
88° C.	$\sigma = 15{\cdot}7f^{0\cdot526}$

A glance at Fig. 31 shows how much more accurately these equations fit the observations than do the linear equations given by the authors. It is important to notice that the curves of all these equations pass through the origin, i.e. the loss at zero frequency or the d.c. loss is negligibly small. This is what may be expected from the known value of the resistivity of glass. Further, these equations explain Addenbrooke's results. The form of the curves is exactly that indicated by Addenbrooke. Thus it seems probable that in the cases considered, the whole of the loss measured by Fleming and Dyke is due to "after-effect" and takes place in accordance with Schweidler's theory. The results of Schweidler's d.c. experiments gave values of m of $0{\cdot}74$ and $0{\cdot}70$ for two samples of glass at 20° C. He also found that m was not greatly affected by rise of temperature, although the constant β increased very strongly. Now G in the equation

$$\sigma = Gf^m = (2\pi)^m \frac{\pi\beta C}{2\Gamma(m)\cos\dfrac{(1-m)\pi}{2}} f^m$$

is approximately proportional to β, since m does not change very greatly. Thus the above equations derived from Fleming and Dyke's results are also quite consistent with the results found by Schweidler with direct current, since G is found to increase very strongly with temperature, while m decreases but comparatively little. Thus it seems probable from the results of these observers that over the range of power and telephonic frequencies the power loss obeys the law

$$W = Bf^m$$

where f is the frequency, m is an index rather less than 1, and B is a constant, depending on the voltage, size of sample and the nature and condition of the dielectric.

When the whole range of frequencies is considered, including radio frequencies, the results obtained by different observers appear to be by no means consistent. H. J. McLeod * made experiments on glass, pyrex, paraffin and mica over the range of frequencies

* *Phys. Rev.*, 1923, vol. 21, p. 53.

500 ∼ to 1 000 000 ∼ using a bridge method for frequencies up to 3 000 ∼, and the usual substitution method in a resonating circuit for the higher frequencies. He found that the law $W = Bf^m$ held over the whole range of frequencies for all the materials tested, the value of m varying from 0·85 to 0·90. This means that $\tan \delta$ continually decreased as the frequency increased, although the effective conductance always increased with increase of frequency.

A series of measurements at radio frequencies has been made by Schott.* His range of frequencies was 2×10^5 ∼ to 10^6 ∼ and he tested a number of kinds of glass, ebonite, press-spahn and compressed amber. Over this range of frequency he found that $\tan \delta$ did not change very greatly. In general it increased slightly as the frequency increased, though sometimes the change was in the opposite direction. Again, Dellinger † and Preston have given the results of a great many observations on the loss angle of insulating materials of the laminated pheno-methylene type, over the frequency range 3×10^5 ∼ to 6×10^4 ∼. They also found that variations in $\tan \delta$ were small over this range, and that it generally increased with increase of frequency, though sometimes it decreased. Although Schott made no measurements at low frequencies, he gives the results of a few observations at low frequencies made by other observers on materials similar to those he used (e.g. glass of the same grade and composition). In all these cases the value of $\tan \delta$ is higher at the lower frequencies.

Contrasting strongly with these results are those of Bairsto,‡ already mentioned. He found that $\tan \delta$ for paper, glass, gutta-percha, etc., varied greatly with frequency, reaching a maximum value somewhere in the region $0 \cdot 2 \times 10^6$ ∼ to $0 \cdot 7 \times 10^6$ ∼. This maximum value of $\tan \delta$ was usually much larger than the value at low frequencies. Lübben § has given a series of results for telephone-cable paper at telephonic frequencies, and these are found to agree fairly well with the formula $W = Bf^m$, whilst the same formula was given by Granier ‖ for observations made on poor condensers at low frequency.

Summarizing, the variation of power loss with frequency over the range of power and telephonic frequencies is usually given by the formula $W = Bf^m$, where f = frequency, and m is less than 1. If the frequency range is small, the law $W = B'f$ may be used as an approximation, in order to simplify calculation. Where these laws apply, the power loss is probably entirely due to dielectric "absorption" or "after-effect." At radio frequencies the value of $\tan \delta$ due to "after-effect" is smaller than at telephonic frequencies if the above law still holds, but the experimental results available at radio frequencies do not appear to be sufficient to decide whether or not the laws are the same as at the lower frequencies, though probably they are not. It is interesting to note, however, that all the results are possibly capable of explanation in terms of Wagner's theory, discussed in Section IV, though this explanation is far from being established.

If the dielectric losses in any particular case are due to absorption, then changes in the losses with frequency should be accompanied by corresponding changes in capacity. Bairsto * examined the results of Fleming and Dyke † and pointed out that the change in capacity ΔC, over a given range of frequency, was a definite function of the a.c. conductivity. He states that

$$\frac{\Delta C}{C}$$

is proportional to b, where b multiplied by the frequency f represents the main part of the a.c. conductivity σ, i.e.

$$\frac{\Delta C}{Cb}$$

is a constant, which is independent of the temperature of the dielectric and its state of moisture content. It is easy to show that this relation is simply an approximate form of an equation which can be derived from Schweidler's work. We have seen that this leads to the formulæ ‡

$$\frac{\Delta C}{C} = \beta \omega^{m-1} \Gamma(1-m) \cos \frac{(1-m)\pi}{2}$$

and

$$\sigma = \beta C \omega^m \frac{\pi}{\Gamma(m) \cos \frac{(1-m)\pi}{2}}$$

Schweidler found that the index m varied very little with temperature, but that the changes in β were enormous. Taking the ratio of

$$\frac{\Delta C}{C} \quad \text{and} \quad b = \frac{\sigma}{f} = \frac{2\pi\sigma}{\omega}$$

we find

$$\frac{\Delta C}{Cb} = \frac{1}{2\pi C} \times \frac{\Gamma(1-m)\Gamma(m) \cos^2 (1-m)\frac{\pi}{2}}{\pi}$$

which, since $m < 1$, reduces to

$$\frac{1}{C} \cdot \frac{\tan \frac{1}{2} m\pi}{4\pi^2}$$

For a given substance, this ratio will vary but slightly with changing conditions, although the changes in

$$\frac{\Delta C}{C}$$

and σ may be very large, since each contains the term β. Thus the relation pointed out by Bairsto merely confirms the idea that the losses measured by Fleming and Dyke were all due to absorption. When we examine

* Schott: *Jahrbuch der Drahtlosen Telegraphie*, 1921 vol. 18, p. 82.
† Dellinger and Preston: Technological Paper, *Bureau of Standards* vol. 16, No. 216, p. 502.
‡ Bairsto: *Proc. Roy. Soc.*, 1920, vol. 96, p. 363.
§ Lübben: *Archiv. für Elektrotechnik*, 1921, vol. 10, p. 283.
‖ Granier: *Rev. Gén. de l'Électricité*, 1922, vol. 12, p. 459.

* Bairsto: *Electrician*, 1915, Oct. 15.
† Fleming and Dyke: *Journal I.E.E.*, 1912, vol. 49, p. 3.
‡ Section II, p. 1164.

Bairsto's results, however, we find no maxima of capacity corresponding to the maxima of $\tan\delta$ or σ. Thus it seems probable that at radio frequencies some factor other than absorption is involved.

(ii) *Liquid dielectrics.*—The losses in liquid dielectrics such as oils are found not to vary with frequency like those in solids. Differences between the anomalous dielectric properties of liquids and solids have been discussed in Section II, page 1165. As regards power loss, the most important recent work appears to be that of Pungs.* He measured the losses in transformer oil, castor oil, and paraffin oil, at frequencies of 20 ∼ to 65 ∼ using an electrometer method. For transformer oil and castor oil he found that the power factor was of the order of ½ per cent at 50 ∼, and that the actual power loss was practically independent of frequency. He considered that this power loss was due to conduction, which was electrolytic in type. There was also a small component of power loss which varied with the frequency, but in one case this was definitely traced to impurities. In the case of paraffin oil the power losses were about 10 times smaller than those in the other oils, the power factor being of the order 0·0003. In this case the loss did vary with frequency. It was regarded as consisting of two components, one proportional to the frequency, and one independent of frequency, both being of the same order of magnitude. A. B. Bryan † has given the results of a few measurements on dielectric losses in nitrobenzene and xylene at radio frequencies. In xylene the losses were too small to measure, and in nitrobenzene the loss angle decreased strongly with increasing frequency, suggesting that the loss was mainly due to leakage and not greatly dependent on frequency. McDowell ‡ obtained similar results for castor oil, olive oil, turpentine, paraffin, benzene, toluene and xylene. On the other hand, Fleming and Dyke,§ working with a variable condenser with vaseline oil dielectric, observed a power loss at radio frequencies which increased considerably with increasing frequency. In this case the power loss could not have been mainly due to leakage.

(*b*) *Effect of temperature.*

In the case of certain commercial dielectrics, e.g. varnished cloth, all observers are agreed that the power loss increases very rapidly as the temperature rises. Measurements showing this fact have been made by Rayner,‖ Shanklin,¶ Skinner ** and Bureau †† on varnished cloth. Lübben‡‡ has obtained similar results with telephone-cable paper. This rapid increase of power loss with temperature appears to occur in all porous dielectrics, i.e. dielectrics which contain moisture, and may well be associated with conductivity which is ionic in character. Measurements made by Fleming and Dyke §§ on paper, both paraffined and untreated, show that when the paper is thoroughly dried, not only is the power loss greatly reduced, but it also increases comparatively little with rise of temperature. Fleming and Dyke also found a rapid increase in power loss with rise of temperature in the case of glass, celluloid, ebonite. For mica, pure para rubber, and dry slate, the increase was less marked, whilst for vulcanized india-rubber and gutta-percha the power-loss/temperature curve showed maxima and minima. In the case of gutta-percha the maximum power factor occurred at about − 10° C., the value falling rapidly as the temperature rose from 0° to 50°, while for V.I.R. the maximum was at − 30° C., the value then falling rapidly to a minimum at about 20° C., rising again beyond that point. An important series of observations on commercial insulating materials has been made by K. W. Wagner.* His results are in general agreement with those of Fleming and Dyke. For various grades

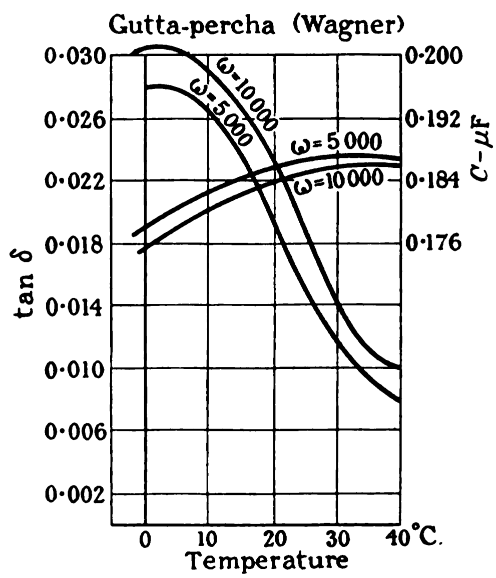

FIG. 32.—Variation of power factor with temperature.

of gutta-percha and balata, over the range of temperature 0° C. to 40° C. the power loss decreased strongly with increasing temperature (see Fig. 32). For pure para rubber there was a slow increase of power loss with rise of temperature over the range 5° to 30°, whilst for vulcanized rubber and ebonite the increase was more rapid, especially at the higher temperatures, 30° C. to 50° C., say. Wagner also gives the results of d.c. observations on the same material at various temperatures, and discusses the significance of the results in terms of his theory (Section IV, page 1179). He gives the curves representing $\tan\delta$ as a function of temperature for a number of different frequencies. For a given substance the curves are of the same general shape, and the curve for any frequency f_2 can usually be obtained from that for the frequency f, by a displacement of this curve on the chart. Wagner points out that the results mean that the probable time constant T_0 decreases strongly with temperature,

* PUNGS: *Archiv. für Elektrotechnik*, 1912, vol. 1, p. 329.
† A. B. BRYAN: *Phys. Rev.*, 1923, vol. 21, p. 399.
‡ McDOWELL: *Ibid.*, p. 371.
§ FLEMING and DYKE: *Proc. Phys. Soc.*, 1910, vol. 23, p. 117.
‖ RAYNER: N. P. L., *Collected Researches*, 1913, vol. 9, p. 75.
¶ SHANKLIN: *Gen. El. Rev.*, 1916, vol. 19, p. 842.
** SKINNER: *Journ. Franklin Inst.*, 1917, vol. 183, p. 667.
†† Bureau, *Bulletin de la Société Inst. des Électriciens*, 1913, vol. 3, p. 669.
‡‡ LÜBBEN: *Archiv. für Elektrotechnik*, 1921, vol. 10, p. 283.
§§ FLEMING and DYKE: *Journal I.E.E.*, 1912, vol. 49, p. 323.

* WAGNER: *Archiv. für Elektrotechnik*, 1914, vol. 3, p. 67.

while the distribution constant b changes but little. When b does change, it appears to increase with rising temperature. For cases in which b remains constant Wagner enunciates the "Law of Corresponding States" for dielectric absorption or after-effect. "The same time law (or frequency law) holds for the 'after-effect' at all temperatures, provided that a unit of time proportional to the time constant T_0 is chosen." This will, of course, apply to both changes of capacity with frequency and to power factor, since both are aspects of "after-effect." It will not hold for power loss due to any other cause than after-effect. The various curves given by Wagner supply many illustrations of this law (Fig. 32).

Schott * has given numerous curves showing the variation of power loss with temperature at radio frequencies for several different kinds of glass. In all cases there is a rapid increase of loss with rise of temperature.

In the case of liquid dielectrics, a very rapid increase of power loss with rise of temperature appears to be general, though the dielectric constant or permittivity generally decreases as the temperature rises. Valuable data are given by Pungs.†

(*c*) *Change of state.*

Closely associated with the effect of temperature changes on dielectric losses is that of a change of state. Waxes and materials of low melting-point are widely used for insulation purposes, and the change in the character of the dielectric losses which occurs on melting is of great interest. Data on the subject are given by Pungs† (at power frequencies), Wagner ‡ (at telephonic frequencies) and Steinhaus § (at radio frequencies). Pungs worked with a mixture of resin and beeswax. He found that in the solid state the power loss was approximately proportional to the frequency (and presumably due to after-effect). It increased with rise of temperature, until the neighbourhood of the melting-point was reached. There was then a sudden drop in the power loss, but with a further rise of temperature, the losses in the liquid increased very rapidly and became independent of the frequency (and thus probably due to conduction, see Fig. 33). Wagner gives data for paraffin, ceresin, and a mixture of the two. He observed the same sudden drop in the losses near the melting-point of the material, though the loss did not appear to be independent of frequency above the melting-point. He also found a drop in the permittivity near the melting-point. Steinhaus also noticed the drop in the losses near the melting-point in the case of the poorer waxes, but for paraffin and ozokerite he did not observe this effect. His value for the power factor of paraffin wax is considerably higher than that given by Wagner, though it is impossible to say whether this is due to the difference of frequency, or differences in the quality of the material. Wagner considers the rapid fall in the power loss in gutta-percha as the temperature rises from about 20° to 40° C. to be connected with the change of state of the material, i.e. softening. Hochstädter * explains the variation of power loss with temperature for high-tension cables in the same way. Clark and Shanklin † have made measurements on a mineral hydro-carbon cable compound, as used for high-voltage cables. Their working frequency was 60 ~, and voltage gradient 16 kV per cm. They found a continuous increase of power factor with temperature over the range 50°–100° C. The permittivity decreased with rise of temperature, but there was a hump on the curve between 50° and 75° C. This was stated to correspond to the gradual change of state of the material. There was, however, no corresponding minimum in the power loss curve, so that it would seem that Hochstädter's explanation

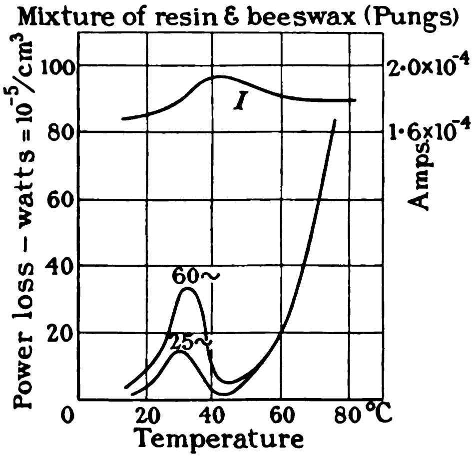

FIG. 33.—Variation of power loss with temperature.

does not apply to every case, or rather that the power loss-temperature curve does not always pass through a minimum value near the softening-point.

(*d*) *Variation of power loss with voltage.*

In Section I it was shown that the expression for power loss is

$$W = V^2 C\omega \tan\delta$$

where C is the effective capacity, and $\tan\delta$ is the tangent of the loss angle, which is in most cases practically the same as the power factor. From this it is obvious that if the capacity and $\tan\delta$ are independent of the voltage, then the power loss is proportional to the square of the voltage. For convenience this is usually referred to as the Square Law. If, on the other hand, the capacity and $\tan\delta$ increase as the voltage increases, then the power loss increases more rapidly than the square of the voltage.

The results obtained by the various investigators who have made observations on this point are very varied, and it is very difficult to form any general conclusions. Several observers have stated that when other conditions are maintained constant (in particular

* SCHOTT: *Jahrbuch der Drahtlosen Teleg.* 1921, vol. 18, p. 82.
† PUNGS: *Archiv. für Elektrotechnik*, 1912, vol. 1, p. 329.
‡ WAGNER: *Archiv. für Elektrotechnik*, 1914, vol. 3, p. 67.
§ STEINHAUS: *Jahrbuch der Drahtlosen Teleg.*, 1921, vol. 18, p. 29.

* *E.T.Z.*, 1922, vol. 17, p. 575.
† CLARK and SHANKLIN: *Trans. A.I.E.E.*, 1917, vol. 36, p. 447.

the temperature), the power loss is strictly proportional to the square of the voltage, at least up to the voltages at which brush discharges begin to occur. Results supporting this are given by Monasch * for glass, ebonite, and certain cables, all tested at 80 ∼. If the high voltage is applied to the specimen for a long time, then the energy dissipated will cause a rise in temperature which may lead to increased losses. Monasch found that an apparent increase of power factor with voltage was often due to this cause, and that it was essential to eliminate any such effect. Peek † found that the square law held for varnished cloth for voltage gradients up to 12 kV per mm. His experiments were made at 60 ∼, working on an impregnated paper high-tension cable. Clark and Shanklin ‡ and Rosen § find that the power factor is independent of the voltage up to a certain critical point, beyond which the power factor increases with increase of voltage. Clark and Shanklin explain this by assuming that there are cracks or bubbles in the filling material in the cable, and that these contain gas or vapour which becomes ionized when the voltage reaches the critical point, and that it is the losses due to this ionization which cause the increase in power factor. Working with celluloid at low frequencies, Addenbrooke ‖ found that the power loss was proportional to the square of the voltage as long as there was no appreciable rise of temperature. At radio frequencies the square law was found to hold by Alexanderson ¶ and Bairsto.** Alexanderson worked at high-voltage gradients (of the order 1 000 volts per mm), and he found that the power factor increased but slightly with voltage until the breakdown point was approached. There was then a rapid rise of power factor, due no doubt to the rise of temperature. In these experiments the sample was immersed in oil to keep down corona losses.

Bairsto's experiment was made with a glass condenser. Using a balance method (see Section III) he found that the balance point was independent of voltage right up to the point at which brush discharges began to take place.

Thus the work of these investigators leads to the conclusion that for solid insulators at low voltages (in which case the losses are practically entirely due to "after-effect" or absorption), the power dissipated is proportional to the square of the applied voltage. If, however, the voltage is raised sufficiently high for ionization and brush discharges to occur, then the power loss increases more rapidly than the square of the voltage.

A case in which it is generally agreed that the losses do not obey the square law is that of porous materials which contain considerable quantities of water, such as untreated paper, cotton, etc. Important pioneer work on these materials was done by S. Evershed.†† He found that the normal conduction current through these materials varies with time, and that the conductance increases as the applied voltage increases, the law being roughly $\sigma = \sigma_0 V^{0 \cdot 3}$, where σ_0 is a constant, and V the applied voltage. Evershed explained this as follows :—

The capillaries in the structure of the material contain moisture, in the form of small drops. Under the influence of the applied field the moisture moves along the capillaries in such a manner that its conductance increases. When the field is removed the moisture returns to its old equilibrium position. Evershed's experiments were all done with constant applied voltage, but when the voltage is alternating there will be a certain part of the loss due to normal conductance, and this will obviously increase more rapidly than the square of the voltage. Wagner * found that this was the case for the cotton insulation on wires especially at low frequencies. Minton,† working with oil-treated pressboard, found that the behaviour of the material with varying voltage depended largely on the amount of moisture it contained. With high moisture content the power factor increased as the voltage increased, which is what is to be expected, but with low moisture content the power factor decreased with increase of voltage. It is interesting to note that for varnished cloth he found the power factor practically independent of voltage up to 280 volts per mil.

It seems probable that the power loss due to conduction increases more rapidly than the square of the voltage in a great many cases other than those in which it is due to moisture contained in the capillaries of fibrous materials. For example, Pungs ‡ found that it was the case for transformer oil and castor oil, though for paraffin oil the Square Law was approximately obeyed. Shanklin § obtained a similar result for transil oil at 60 ∼. In this connection, it is interesting to consider the results obtained for direct current. The experiments of Evershed have already been mentioned. Tedeschi‖ found a similar increase of conductivity with applied voltage for press-spahn and pilit, while Curtis ¶ obtained the same result for a few insulators. H. H. Poole ** working at very high voltages found a considerable increase of conductivity with applied voltage for mica, glass, shellac, and celluloid, and it seems quite possible that this may be the general rule for insulating materials at such voltages. In this case the power loss due to conduction would increase more rapidly than the square of the voltage. As an explanation of these experiments Günther-Schulze †† has advanced the theory that these dielectrics may be regarded as electrolytes in which the ionic mobility is small. At very high voltages the ions move at a sufficient speed to generate other ions by collision with the molecules of the material, and thus the number of ions and therefore the conductivity increases. It may be that this is the explanation of the increase in power factor of high-tension cables at very high voltages

* MONASCH : *Electrician*, 1907, vol. 59, pp. 416, 460, 504.
† F. W. PEEK : *Gen. El. Rev.*, 1915, vol. 18, p. 1050.
‡ CLARK and SHANKLIN : *Trans. A.I.E.E.*, 1917, vol. 36, p. 447.
§ ROSEN : *Proc. Phys. Soc.*, 1923, vol. 35, p. 237.
‖ ADDENBROOKE : *Electrician*, 1912, vol. 68, p. 829.
¶ ALEXANDERSON : *Proc. Inst. Radio Eng.*, 1914, vol. 2, p. 137.
** BAIRSTO : *Proc. Roy. Soc.*, 1920, vol. 96, p. 363.
†† S. EVERSHED : *Journal I.E.E.*, 1914, vol. 52, p. 51.

* WAGNER : *Archiv. für Elektrotechnik*, 1914, vol. 3, p. 67.
† MINTON : *Trans. A.I.E.E.*, 1915, vol. 34, p. 1627.
‡ PUNGS : *Archiv. für Elektrotechnik*, 1912, vol. 1, p. 329.
§ SHANKLIN : *Gen. Elect. Rev.*, 1916, vol. 19, p. 842.
‖ TEDESCHI : *Archiv. für Elektrotechnik*, 1913, vol. 1, p. 497.
¶ CURTIS : *Bulletin Bureau of Standards*, 1915, vol. 11, p. 359.
** POOLE : *Phil. Mag.*, 1921, vol. 42, p. 488.
†† GÜNTHER SCHULZE : *Phys. Zeitschrift*, 1923, vol. 24, p. 212.

noted by Clark and Shanklin,* Rosen and others, and that it is not necessary to assume the existence of bubbles of gas, though the fact that it did not occur at high temperatures goes to support Clark and Shanklin's explanation. They claim that the filling material expands and fills up the cracks or bubbles at high temperature, and thus the ionization loss no longer occurs.

A law other than the Square Law has been given by a number of other observers for various cases. Fleming and Dyke † made observations on a number of condensers at radio frequencies. They found that the power loss was given by a law of the form $W = kV^2 + \gamma$, where γ varied from $0 \cdot 15$ to $2 \cdot 24$. In the discussion on the paper, the authors state that the losses measured include ionization losses, and that the departures from the square law may be due to this. Mould ‡ has made observations at both telephonic and radio frequencies on a number of materials. He gives the same

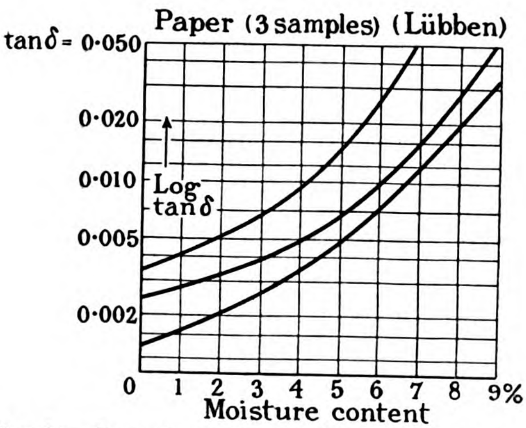

Fig. 34.—Dependence of power factor on moisture.

law as Fleming and Dyke in both cases, though the values of γ only range from $0 \cdot 03$ to $0 \cdot 33$. No explanation of the law is offered, but the author draws the conclusion that the losses must be mainly due to other causes than conductance. In view of the work of Poole and others mentioned above, it appears that the data are not sufficient to justify the conclusion. Unless ionization losses occurred in these experiments also, it does not seem possible to reconcile these results with Bairsto's.

Deviations from the Square Law at power frequencies are described by Skinner § and by Butman,|| for fuller board, micarta sheet, etc. Skinner notes that the index of V in the expression for power loss is often greater than 2, and tends to increase as breakdown approaches. This is possibly a similar phenomenon to that recorded by Poole. On the other hand, Butman found the power factor of fuller board to decrease as the voltage increased, but for micarta the change was in the opposite direction.

(*e*) *Effect of moisture.*

It is a very well-known fact that the absorption of moisture by any insulating material causes a large increase in its direct-current conductivity and in the power loss dissipated under alternating voltage. The capacity of the material also increases. Results of measurements of these effects are given by Lübben * for telephone-cable paper (see Fig. **34**). The variation of capacity, tan δ, and d.c. conductivity, with percentage moisture content is investigated in great detail. The increase of tan δ, and therefore power loss, becomes more rapid as the moisture content becomes greater than about **4** per cent. Minton † found a similar result with pressboard. Wagner ‡ has also given data for the increase of tan δ with moisture absorption for paper, and for wire insulation (silk and cotton, etc.). He shows that the use of cotton covering on a wire causes a large increase in power loss on account of its power of absorbing moisture. Fleming and Dyke § also give information as to the effect of moisture on paper, etc.

Another well-established fact is that surface leakage across an insulating material is largely dependent on moisture condensed on the surface, and is, therefore, largely influenced by atmospheric humidity. Valuable data on this point are given by Curtis.|| Addenbrooke ¶ has found that in the case of alternating voltage the surface leakage is much greater than for constant voltage, the explanation probably being that the moisture stands on the surface in small drops, and not in a continuous film, and thus Maxwell's theory of a laminated dielectric applies (see Section IV). This surface leakage will correspond to a certain power loss, which will take place even in the case of insulating materials which do not absorb water.

It is obvious that all substances which absorb water must be of heterogeneous structure, and thus they must exhibit the phenomena of absorption and power loss in accordance with Maxwell's theory. Using the known values for the dielectric constant and conductivity of water, Meyer ** has attempted to show how the observed data of power loss and absorption are consistent with Maxwell's theory, assuming water to be the most important constituent. Owing to the complexity of the problem, only a rough approximation can be expected. Certain results given by Meyer appear to correspond with the theory in the simple form taken, but in general the evidence is by no means convincing.

Compared with the average dielectric, water possesses a very high dielectric constant, and a very high conductivity. If, therefore, a particle of water contained within an insulating material is placed in an electric field, it will be acted on by mechanical forces tending to elongate it in the direction of the field. Actions of this nature were first investigated by Evershed †† in a

* Clark and Shanklin: *Trans. A.I.E.E.*, 1917, vol. 36, p. 447.
† Fleming and Dyke: *Proc. Phys. Soc.*, 1910, vol. 23, p. 117.
‡ Mould: *Beama Journal*, 1923, vol 12, p. 337.
§ Skinner: *Journal Franklin Inst.*, 1917, vol. 183, p. 667.
|| Butman: *Electrical World*, 1918, vol. 71, p. 812.

* Lübben: *Archiv. für Electrotechnik*, 1921, vol. 10, p. 282.
† Minton: *Trans. A.I.E.E.*, 1915, vol. 34, p. 1627.
‡ Wagner: *Archiv. für Electrotechnik*, 1914, vol. 3, p. 67.
§ Fleming and Dyke: *Journal I.E.E.*, 1912, vol. 49, p. 323.
|| Curtis: *Bulletin Bureau of Standards*, 1914, vol. 11, p. 359.
¶ Addenbrooke: *Proc. Phys. Soc.*, 1912, vol. 24, p. 286. *Electrician*, 1922, vol. 88, p. 64.
** Meyer: *Verh. Deutsch. Phys. Gesell.*, 1917, vol. 19, p. 139.
†† Evershed: *Journal I.E.E.*, 1914, vol. 52, p. 51.

paper previously referred to. He showed that as a result of this, the d.c. resistance of fibrous insulators is a function of the applied voltage. Du Bois * has also called attention to this phenomenon. He points out that a drop of water, such as has been considered, would elongate into a filament which might in time bridge the electrodes. These movements of the water would cause alterations in capacity and conductivity, and this is put forward by Du Bois as an explanation of absorption and residual charge. Considering the power loss in an alternating field, he points out that in the case of filaments which bridge the electrodes the power loss will not depend on the frequency, but when they do not bridge the electrodes the loss will vary with frequency. This, of course, follows from Maxwell's theory. Further, he states that a filament carrying current may be at a higher temperature than the surrounding dielectric, and that if the temperature of the filament increases with increase of applied voltage, then deviations from the Square Law may be expected. Evaporation may lead to a breaking up of the filaments, and thus there may be a change in the power loss-voltage curve at some critical point. The conception introduces many variable factors, and it is difficult to see to what extent they will affect the behaviour of the material, but it seems probable that materials containing moisture will obey different laws from those which do not. Hayden and Steinmetz * have considered the bearing of such actions on the breakdown of insulation under high voltage.

* Du Bois: *Journal A.I.E.E.*, 1922, vol. 41, p. 688.

* Hayden and Steinmetz: *Journal A.I.E.E.*, 1923.

DISCUSSION ON

"THE ECONOMICS OF LAMP CHOICE." *

Mr. W. J. Jones (*communicated*): The author deals with a matter which has been familiar to lamp manufacturers and those interested in B.E.S.A. Specifications for many years, and it is a pity that while the theoretical considerations are generally sound they have not a greater practical bearing. The illustrations which have been cited are purely theoretical, and may in some cases, as a consequence, be misleading. The author has pointed out two considerations in the algebraic solution, namely that of a lamp which is either over-run or under-run and, secondly, the point of view of a lamp designed to give a definite candle-power. This last does not meet with modern practice in which the wattage of the lamp is made the basic feature, so that both graphics and calculations require some modification. The author mentions the question of making the price of lamps proportional to the size in watts. Surely this is only to meet a purely theoretical consideration and does not in any way take into account the economics prevailing in lamp works where the cost of manufacture depends not only on the size of lamp but also on the number of that particular size manufactured. Regarding the suggestion which is made of grading lamps for dear, medium-price and cheap energy, I would suggest that this is entirely outside the province of the lamp manufacturer, but, assuming that it were advisable for the lamp manufacturers to take some action, it would involve increasing the number of types of lamps already on the market from some 2 000 to 6 000; as this would reduce the quantity manufactured of any particular type of lamp, the cost of the lamp would inevitably be increased.

Mr. D. J. Bolton (*in reply*): There is no suggestion in my paper that the lamp price could be altered and made proportional to the size. All that is suggested is that the normal rating could be made dependent upon the size (and possibly upon the price), i.e. a 60-watt lamp should be rated to have a shorter life and a higher efficiency than it now has, while a 20-watt size should have a longer life and lower efficiency than at present.

The other point raised, as to the number of types required in the event of lamp grading to suit energy price, is, of course, a perfectly valid one. It is exceedingly difficult to say what would be the all-round effects of such a step, but the saving to the consumer would be so considerable that if any large manufacturer or group found it possible to overcome the initial difficulties, such an enterprise might prove extremely popular and successful.

The paper was particularly intended to represent the point of view of the lamp user. It is true that the modern rating is in watts, but to the user that is merely a means to an end—he desires a definite quantity of illumination and when he asks for, say, a 40-watt lamp it is because he associates this with a particular candle-power.

* Paper by Mr. D. J. Bolton (see page 844).

DISCUSSION ON

"THE DESIGN OF ELECTRICAL PLANT, CONTROL GEAR AND CONNECTIONS FOR PROTECTION AGAINST SHOCK, FIRE AND FAULTS." *

SCOTTISH CENTRE, AT GLASGOW, 13 APRIL, 1926.

Mr. J. Henderson : I am in entire agreement with the principles laid down by the author, and consider that the practice of enclosing all conductors in an earthed metal sheath should be pushed to its utmost limit. The application of this principle to the power station busbars and switchgear is a much more satisfactory answer to the question of continuity of supply than the American idea of phase isolation. The duplication of busbars in the power station and at the important feeding points is to be commended, but it should not be necessary to have a special busbar as a stand-by. The sectionalizing which is now standard practice on all large systems should prevent any difference of opinion on this point, as one section of busbars may be employed as the stand-by or hospital bar for the two others, or conversely two spare bars are available for each section in emergency. This arrangement is possible with either the star or ring method of connection, but I have a strong preference for the star method with each section connected to a reactance bar through reactances which will pass the economical load of the smallest machine where the ratio of this to the largest is not less than about 0·5. On the question of the value of parallel reactances, the author might with advantage have stated whether this value should be greater than, equal to, or less than that of the inherent reactance in the generators, based on the section load. The reactances should only be installed as a means of sectionalizing the system and not as a link between sections through which a large amount of power is to be transmitted. It should be laid down as a principle that the exchange of power should be kept down to as low a limit as is compatible with efficient running of the generators. Unless in special cases, the use of series reactance external to the alternators cannot be regarded as advantageous, and may lead in the end to a great deal of difficulty and confusion. Circuit breakers capable of opening under the worst possible conditions without the use of series reactance, should be installed at the power station and main feeding points, and if this rule is adhered to the duplication of main circuit breakers can only be considered as an unnecessary refinement. I am greatly in favour of deciding the size of circuit breaker in accordance with the maximum kVA to be broken rather than risk a short-circuit which may do more than destroy the switch affected. The maximum kVA should be the criterion, and not any smaller value which is dependent on the time taken by the circuit breaker to open. I have no quarrel with making a circuit dead before changing over, but design of the change-over gear should be subordinate to speed of operation. It is obvious that screwed plugs are not conducive to quick action, and a much better arrangement is that of an auxiliary change-over switch in the cowl of the circuit breaker, mechanically interlocked to prevent operation unless the main circuit breaker is racked out. Operating engineers will all be in favour of any design which simplifies and reduces the number of operations to be carried out in effecting a change-over. The auxiliary supply should be taken off the reactance tie bar and may be suitably duplicated by a house turbine feeding continuously on to the low-tension auxiliary busbars. This would make unnecessary the elaborate change-over scheme suggested by the author, and I am not in agreement with any attempt to change over the auxiliary supply to the unit system every time a generator starts up. The house turbine has additional advantages in connection with heat balance control, but these are beyond the scope of the paper. The use of the modern reverse relay in connection with auxiliary supply should effectively prevent the complete shut-down, due to failure, of anything except the auxiliary busbars on the low-tension side, and special attention should be paid to the design of these to prevent trouble from this cause. In connection with protective gear, "stability ratio" as defined by the author is an excellent term, but I do not think it goes far enough. It is really only a relative term and is dependent on too many conditions to be of any general use. There is no reason why an absolute value should not be introduced giving an absolute comparison between different types of protective gear. The operating current in amperes stated with the "stability ratio" probably meets the case sufficiently well for all practical purposes, but the statement of the one without the other is of no value and contains no useful information. The majority of operating engineers will not agree with the tendency to cut out the earthing resistance. This tendency nowadays, and the suggestion introduced by the author to decrease the value considerably, probably arises from the inability to obtain low enough fault settings combined with high stability ratio. There are protective systems in use as applied to generators which will give stable operation and a 5 per cent setting, and I do not think that the earthing resistance should pass more than 1 000 amperes. This should enable adequate protection to be given to all except the very largest generators. I should have thought that in advocating a metal-clad supply system the author would have favoured slightly higher values of earthing resistance, but I agree that it is better to have a solid earth than to allow too small an earth fault current to flow. In the actual protective gear itself the onus of supplying gear working on sound principles, and with component parts above suspicion, lies on the manufacturer. The works tests are most important for eliminating faulty components. Balance tests for current transformers should be opposition tests and not differential tests,

* Paper by Mr. H. W. Clothier (see vol. 63, pp. 425 and 1023).

thus ensuring that a pressure test is applied between turns and layers. Serious mistakes in wiring are mostly due to a lack of co-operation between the works staff (who may understand the principles) and the erection staff (who usually do not). I am most interested in some of the causes of unbalancing detailed by the author. The causes of instability are often difficult to determine and, where local conditions are at fault, each problem will require a separate solution. Induction from overhead lines is very serious and will require well-insulated pilot cable to prevent accidental short-circuiting of the pilots due to induced voltage. This is apart from the difficulties with capacity currents or circulating currents through the earth connection.

Mr. A. P. Robertson : The author attempts to show the advantages of the solidly interconnected system in order to reduce to a minimum the amount of switching on supply systems, and says that the plant should be linked together in one common copper network. Such a system may obviate a certain amount of switching, but when a shut-down takes place at the power station the difficulty is to get all the apparatus into commission again if the system is solidly interconnected. The system ought to be capable of being sectionalized quickly. The solidly connected system is quite good in many ways, but disconnecting links should be provided and these should be operated mainly by the power station engineer. What I mean is that if a station is carrying a load demanding the operation of four machines, and an interruption occurs, in starting up again, when the first machine is switched on the bars, the whole of the load comes on and is too much for the machine, so that there should be some method of putting a machine on a section only. The duplicate busbars are certainly wanted occasionally, but I think that all busbars should be used. I agree with Mr. Henderson that there is no necessity for a set of busbars lying idle ; all the copper should be used. As regards the system of plugs, I have not had any personal experience of working these, but I think that wherever possible a solid connection ought to be used in place of screwed plugs. There is always a danger of a screwed plug not being screwed right home, in which case there is a possibility of heating just at the contacts. Trouble is then experienced with compound leaking at the joints. It is not a very common experience, but still it has been observed, and the fault has been traced to this cause. The author also spoke of a system in which the whole of the cabling between the generators and the switchboard was solidly earthed. In my experience, the trouble, in long cables earthed at each end, would be currents in the lead, and in some cases an insulator has had to be inserted at one point in the lead sheathing. In ordinary short cable it does not matter, but where the cable is of any considerable length it is necessary to prevent eddy currents. I was very interested in the size of the switchgear in the American power stations, and in the British power stations using the same size of breaker capacity. The rating of switchgear is very loosely defined by switchgear makers. Switches are rated at 50 000, 100 000 or 200 000 kVA, and after all, in many cases, these are only nominal ratings, because the makers have had no means of testing their products to destruction, or even with any great capacity behind them. Until recently, there has been nothing very definite on which to base the capacity of switches, but this state of affairs is now being rectified. The author also mentioned the use of charging resistances in switches. My experience has been that they are more dangerous than advantageous and ought to be taken off. I had never had any trouble before which could be traced to switching in, but, after the resistances were fixed, in many switches a lot of trouble resulted. The resistances heated up and a sort of deposit was formed which came out and got amongst the switch contacts. Whether it was due altogether to the material of which the resistances were composed I cannot state definitely, but since the resistances were taken off no trouble has been experienced. The oil switch-fuse has many uses but its size is a drawback. It occupies a great deal of space, and it is also very high, so that a high station is required to house it. Except for a slight difference in cost, the switch is preferable. I was interested in the one switch substation shown on the lantern slide. Where many substations are connected in busy centres it is imperative to keep the cost down, so that the switchgear should be reduced to a minimum. At the same time I do not agree with cutting it down and sacrificing any of the security. On a feeder on which there are half a dozen substations, it is only necessary to protect it by overload at each end, and to insert disconnecting links in each substation.

Mr. E. Seddon : I am one of those who have gradually been converted from the belief that the cellwork type of switchgear was the best form of construction from the operating engineer's point of view, to favouring the system of enclosing conductors in metal casings such as advocated by the author. I have spent a considerable amount of time developing designs for interlocking portions of switchgear of the cellwork construction until I found myself drifting unconsciously towards the ironclad design, which seems to point to the fact that this is the proper line of progress. There are, I think, three essential features required of any switchgear to meet the views of most engineers operating large plant. These are :—(1) That the switchgear shall be so designed as totally to enclose and seal with a suitable insulating medium all permanent conductors, and only those parts subject to wear and deterioration should be made detachable ; (2) that the design of switchgear will only permit of its operation in proper sequence to ensure that any circuit carrying e.h.t. energy cannot be interrupted except through a quick-break oil switch ; and (3) that any failure of insulation should immediately become an earth fault and the apparatus isolated as a result of such an event happening. I believe that the best layout of switchgear would result from a design involving a number of separate switch-houses, each building containing a machine panel with its complement of feeders. The busbars of the separate sections would be coupled together through cables and hand-operated oil switches of low breaking capacity.

Mr. D. Martin : The Electricity Commissioners' Report for 1924 shows that 6 681 500 000 kWh were generated in the United Kingdom during the year 1924. Of this amount I calculate that at least 1 810 000 000

kWh in 1924 and some 2 200 000 000 kWh in 1925 passed through metal-clad switchgear of the author's design. In other words, at least a third of the current generated in the United Kingdom is controlled by switchgear of the metal-clad type at some point or other in its course from the generating stations to the e.h.t. substations. What are the reasons for this phenomenal progress? To my mind the following appear to be the principal reasons:—

(1) Shocks and burns from accidental contact with live conductors are eliminated.
(2) Enormous saving in building costs and building space.
(3) Reduction of cleaning costs by about 90 per cent.
(4) Absence of fire risks in clearing short-circuit or earthing faults on the transmission system, due to metal-clad enclosure at earth potential.
(5) Impossibility of drawing an arc and its resulting destruction in the case of inadvertently opening a circuit on load, mainly due to the elimination of air-break isolating switches.
(6) Elimination of risk to human life and plant in the event of mistakes in operation, especially at times of emergency.
(7) Metal-clad construction limits injury, due to faults developing on the switchgear itself, to the unit concerned, without affecting adjacent units, provided the metal enclosure is properly earthed.
(8) The stronger mechanical construction available eliminates the explosion risks of the destructive forces developed in the oil tanks in clearing severe faults on the system.
(9) Simplicity of construction and the marked engineering features of the design.
(10) The absolute interchangeability of switches, class for class, which reduces the number of spares to be carried to a fraction of what it used to be. In Glasgow, for instance, only one switch of the 6 600-volt class "C1" type is carried, though there are over 1 000 of this class in commission.

This phenomenally small proportion of spares is sufficient proof of the adequacy of the type used in Glasgow and the perspicuity of their engineers. We have in Edinburgh an example of duplicate switches and duplicate busbars. One half of the switches only are in commission at one time. Surely this is a wasteful method. If the primary object of duplicating the switches were to speed up the time of changing over from one busbar to another without breaking circuit, the time element again becomes of importance, for it is essential that both busbars must first be running in parallel and that takes time. If the object is to have a stand-by switch, then it surely points to a lack of confidence in the switches employed, and the money spent on two switches could have been utilized in perfecting one of greater reliability, with a resultant saving of 25 or more per cent on the switchgear contract. Again, if the duplicate switch is for use in the event of the failure of its partner on load, one of the claims of the advocates for duplicate switches is weakened, for under a failure or "fault" condition the circuit is opened whether we wish it or not, and by the time it has been discovered whether the fault is in the switch or on the outer circuit more time would have been lost than in the case of the system advocated by the author in Figs. 7, 8 and 14. Further, the system advocated by the author eliminates the use of isolating links on which there is always the risk of mistakes during the hurry of an emergency. Within the past three weeks a skilled man was fatally injured by shock on a cellular-type board in a substation. He obviously must have forgotten to withdraw the isolating links on the "live" tails of cables connecting the two halves of the board in question, during the prosaic operation of routine cleaning of the gear. My experience compels me to air the view that this open-cell type of gear should be prohibited now that we have draw-out metal-clad gear. In attacking the problem of protective gear and discriminating devices we seem to have lost the original objective of our search. Whilst I do not neglect research along the lines which we have developed so far for discriminating devices, I think the question of research into fuses seems worthy of some attention. The fact that a fuse is an ideal form of overload protection is sometimes overlooked, for it can be fused to blow at full load or any percentage above full load or before the load reaches the danger point in the curve and before a cycle has had time to develop. Fig. 18 illustrates the case. Of course I fully appreciate all the physical and technical difficulties inherent in fuses, but my point is that we should not allow the subject of research into adequate fusing to be wholly dropped and forgotten. I am in favour of earthing the gear while men are working, on the lines advocated by the author, and with regard to the draw-out type now made by so many manufacturers there is no simpler method than that illustrated in Fig. 24. Personally I prefer to close the earth circuit by means of one of the circuit breakers under oil, as indicated. All the risks of loose ends and the creation of further faults are eliminated by this very simple method, and it is adopted as routine practice on at least six of the larger power supply systems in Scotland. In this connection there is still room for a suitable and reliable portable instrument to indicate whether an innocent looking piece of gear is dead or not. With regard to switchgear in mines, a subject in which I am specially interested, I think the consensus of opinion is now focused on the following ideals:—

(1) Metal enclosure of all live conductors. Manufacturers and the mines inspectors have between them seen to this fairly well. In underground workings without illumination it is a crime to have exposed live parts.

(2) There should be no enclosed air spaces. All spaces should be compound-filled except where there may be moving parts, such as switch contacts; in this event oil immersion is sufficient. Air-break gear should not be allowed. Even in non-fiery mines there is always the risk of pockets of gas being liberated at some time or other in the life of a mine.

(3) In the matter of oil-switch or circuit-breaker tanks or containers for use underground, it is advisable to use boiler plate steel in preference to cast iron. In

clearing severe faults the container is liable to be blown to pieces if it is of the more fragile cast-iron type, and the risks underground are already sufficient without adding this further unknown terror to them.

(4) The joint between the tank and the heavy switch hood should be of the flame-proof type for the same reason as in No. (2) above.

(5) Isolating switches underground should be avoided on account of the risk of earthing them in the semi-dark conditions. The only way to obviate this risk is to utilize the "draw-out" switch.

(6) In the matter of automatic trips, it is advisable to have these locked up to prevent any but the authorized electrical engineer operating them. The simplest way to obtain this is to put them inside the oil switch tank. This further ensures that they can only be adjusted while the parts are dead; this is highly desirable underground.

(7) A very important statutory requirement in regard to colliery work is an easy means of indicating earth leakage. The simplest method of satisfying this requirement is to adopt the "core balance" system of protection, which trips when an out-of-balance fault, such as an earth fault, develops in any one of the three cores of the three-phase system. The faulty circuit would thus be switched out until the authorized engineer switched on again, presumably after he had located and removed the fault. What better system of indication can there be? Here again the metal-clad gear lends itself as an ideal housing arrangement for the core-balance transformers. Recent intercourse with numerous American engineers also indicates that the advantages of the metal-clad proposition are rapidly finding favour in the United States.

Mr. F. H. Whysall: Although one can speak very highly of the type of switchgear most favoured by the author, there are other forms of switchgear which have advantages one would be wrong to ignore. To-day we have such satisfactory service from switchgear and protective apparatus generally, that to boast of immunity from breakdowns of alternators and substation plant, as I have heard manufacturers' representatives do, is giving credit for improved conditions due really to improved switchgear and protective apparatus. Present-day switchgear disconnects a fault so quickly that the plant is not subjected to the same stresses. One of the speakers in the discussion mentioned the solid system of distribution, and the systems of protection by interconnecting apparatus. We are all in favour of simplification if we can justify it by experience and by the apparatus which we have at our command. I can remember operating switchgear similar to that described by Mr. Martin. Some early types of switchgear were very crude, and some were very elaborate in design. I have often wondered whether a study of some of the old designs, such as the Geipel switch pillar, would not be of assistance when considering new problems.

Mr. H. W. Clothier (*in reply*): The acceptance and support of the general principles of the paper is the tenor of the discussion. These principles have in a very large measure been initiated in demand and developed under the service conditions of this city (Glasgow). By the adoption of metal-clad switchgear for substation equipment and of the 20 000-volt installation at Dalmarnock power station, this municipality has done much for the progress of switchgear design.

The previous discussions and replies in the *Journal* (1925, vol. 63, pp. 446 and 1023) deal with some of the points of detail. For example, in line with Mr. Henderson's plea for a further definition of stability for protective gear, I have made a recast of the proposals (see vol. 63, p. 1033) and have applied this to four types of protective gear (vol. 63, p. 1036). Mr. Henderson prefers to take the supply to the generator auxiliaries off the reactance tie-bar, as this avoids the change-over after the generator has started up. The auxiliary transformers would, however, have to be coupled to these busbars by circuit breakers. The advantage of the unit system is that one main panel suffices to control both the generator and its unit auxiliary transformer; and, furthermore, one system of protection covers the two.

Mr. Henderson and Mr. Robertson both deal with the problem of linking up the sections of a system. The subject requires more time than is now available, but it seems to me that the whole system should be solid, in so far that all copper is in service at the same time and that faults are cut out as they occur by means of automatic protective gear. The size of reactances (where necessary) on the larger system is controlled by the breaking capacity of the circuit breakers installed in the power stations and on the system. When the circuit breakers are large enough to dispense with the aid of reactances a minimum amount of operation is required with changing conditions of load. On the other hand, when it is inconvenient to have the circuit breakers large enough to deal with the load in its entirety, reactances become most useful for interconnecting the plant and network arranged in sections.

I realize that there must be section switches, as Mr. Robertson points out. The question as to whether these should be hand-operated or automatic is important, and is one for the operating engineer to determine in conjunction with the lay-out and operation of the plant as a whole. I should prefer automatic operation on the occurrence of faults.

Mr. Martin mentions the need for further consideration of fuses as discriminating devices. Fuses certainly have some most desirable characteristics. When used to protect a small supply taken from a large network, the switch-fuse illustrated in Fig. 27 will, owing to the fuse's great rapidity of action, clear a short-circuit before the latter has had time to rise to its maximum severity. Unfortunately, when fuses are used as a substitute for reactance the current-limiting effect under short-circuit just referred to is often lost, since the ratio of the short-circuit current available to the normal current transferred through the fuse is insufficient to produce the necessary rapidity of operation. Their use for this purpose is therefore restricted to cases where the transference of power is small in proportion to the power available.

Mr. Sedden's comments are most opportune. I think that his views on switchgear development are typical of those of many experienced observers and users,

particularly in regard to the course indicated by the study of the sequence of interlocked operations to avoid errors in manipulation.

Mr. Whysall has hit upon a curious fact. One of the earliest forms of high-tension switchgear was of a metal-clad pillar type. About 1894 this began to be replaced by slate cell-type gear. Had an endeavour been made at that time to improve upon the pillar construction, we might have come much earlier to metal-clad construction.

PROCEEDINGS OF THE INSTITUTION.

744TH ORDINARY MEETING, 22 APRIL, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m. He reported the death of Sir Henry Mance, LL.D., C.I.E., Past-President, and a vote of condolence with the family of the deceased was carried, the members standing in silence.

The minutes of the Ordinary Meeting held on the 8th April, 1926, were taken as read and were confirmed and signed. Messrs. I. H. Jenkins and E. W. Moss were appointed scrutineers for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows :—

Elections.

Members.

Cusworth, James.
Innes, William.

Associate Members.

Mackay, James Arthur, B.Sc.
Seth, Shankar Dayal, B.Sc.

Graduates.

Banerji, Srish Kumar, B.A., B.Sc.
Barrar, Sydney John.
Bourn, Leslie Edwin A.
Chauhdri, Ghulam Kadir.
Cook, Ernest Henry.
Cooper, John Ashton J.
Creswick, Philip.
Hartland, Sydney.
Jacob, John.
Kerr, Albert Edward.
Kilpatrick, James Stevenson.
Kitching, Donald Albert.
Lyne, Robert Habby.
Mill, Eric Sidney.
Milward, Frederic Andrew.
Mirchandani, Toloram J., M.Sc.
Prabhu, Manjeshwar Govinda, B.E.
Prosad, Bhagwat, M.Sc., B.L.
Roberts, Albert.
Robey, Leslie John.
Ryan, Louis.
Suri, Kishen Das.
Tennison, Alfred John.
Tree, William George.
Williams, Daniel John.

Students.

Allen, Charles Vivian.
Barkwith, Sidney.
Bennett, William Clifford.
Broderick, John.
Buxton, George Edward.
Clarke, James Blasdale.
Collett, William Alfred.
Cooper, Walter Dunbar.
Dixon, Irving Blaiklock.
Dixon, William Garnet E.

Students—continued.

Evans, William Arthur.
Flint, Ernest Frederick.
Francis, Arthur.
Gill, Frederick William.
Goodchild, Ronald Frank.
Gould, Robert Howe (Jun.).
Griffiths, Norman Weddell.
Gulati, K. Badri Nath.
Hinton, Cyril Herbert.
Kember, Stanley.
Little, Eric Charles.
McClelland, William Andrew.
Mhatre, Govind Keshavrao.
Montgomery, William John.
Mundie, Colin Macpherson.
Nicol, Colin Traquair.
Orr, James.
Palmer, Frank Henry G.
Richardson, Henry.
Saunders, Hector Douglas E.
Serby, John Edward, B.A.
Sharma, Ilam Chand, B.Sc.
Skelcher, Frank William.
Smith, Leslie.
Sumner, Walter.
Thomson, Murray Forbes.
Wardle, Granville Ebhorn.
Whelan, Alfred John.
Widdup, Francis Alan.
Widger, Leslie.

Transfers.

Associate Member to Member.

Cohen, Bertram Sydney.
Dixon, Edwin Henry, B.Sc.
Gow, Alexander George.
McLachlan, Dugald Henderson.
Nicholson, John Hedley.
Odam, John Harold.
Pontet, Bernard.
Sillar, Harold MacKnight.
Taylor, John Lyon.
Williams, Frederick Herbert, B.Sc.Tech.

Graduate to Associate Member.

Charles, Norman Henry, B.Sc.(Eng.).
dos Ramos, Herculano Lourenco.
Gibbs, William Reginald.
Hall, Harry, B.Sc.Tech.
Jones, Reginald Hugh, M.Sc.

Student to Associate Member.

Broughall, John Alan, B.Sc.(Eng.).
Cash, Harry Hutchinson.
Fowler, John, B.Eng.
Gallon, William Anthony.
Gooch, Leslie John.
Hewitt, John Leslie.
Johnson, Francis Hannam.
Lywood, Wallace Drake M.
Shephard, Alger George.
Trutch, Charles Joseph H., B.Sc.(Eng.).
Wadlow, Donald Leslie.
Warren, Wilfred Ernest, B.Sc.(Eng.).

Student to Graduate.

Battersby, George Herbert, B.Sc.(Eng.).
Bayley, Godfrey George.
Birt, Ronald, B.Sc.(Eng.).
Bourne, Percival Edwardes.
Colebrook, Hector Frank, B.Sc.
Collier, Harold.
Davies, Bertram Jones.
Duthie, George Ferguson, B.Sc.
Elliott, Harold John.
Hall, Maitland Heseltine.
Kingdon, Thomas Karl.
Manning, Clifford Breillat.
Moseley, Ernest Gower.
Sharma, Banwarilal, B.Sc.
Shilson, Leslie James.
Simpson, Alexander Victor.
Stainsby, James William.
Standring, Ian William, B.A.
Stewart, Ian Dunlop.
Taylor, Louis Norwell.
Tyler, Leonard Benjamin.

Messrs. P. M. Baker, A. M. Coombs and A. F. Harmer were appointed scrutineers of the ballot for the election of new members of Council.

The President announced that, in view of Col. Crompton's absence in America in connection with the International Electrotechnical Commission, the presentation to Col. Crompton of the Faraday Medal had been postponed until the 24th June.

Sir J. J. Thomson, O.M., M.A., F.R.S., then delivered the Seventeenth Kelvin Lecture entitled " The Mechanics of the Electrical Field " (see page 721).

The President : It is my very great pleasure to move a hearty vote of thanks to Sir Joseph Thomson for the exceedingly interesting Kelvin Lecture that he has delivered. Though many of us perhaps could not follow all the intricacies of the atom that he has explained to us, I think that we shall be able to gather a very good idea of the wonderful line of thought which physicists are now following.

Dr. A. Russell : I have very great pleasure in seconding the vote of thanks. I have heard many Kelvin Lectures, but I have never heard one so interesting and wonderful. I had the privilege of being a pupil both of Lord Kelvin and also of Sir Joseph Thomson. There are one or two points of resemblance between them. They were both Second Wranglers, and they both impressed their fellow students very much with their ability. In my freshman's year at Cambridge in 1882 the mathematical lecturer told me of the great physicists and mathematicians that were there. He mentioned Lord Rayleigh, Stokes, Cayley and others. He also said that there was a young man, Thomson, working at the Cavendish Laboratory who was a second Newton. That was prophecy better than he knew, because in 15 years' time Sir Joseph had discovered the electron. Sir Joseph has followed Newton and has given us a corpuscular theory of light which is very much more wonderful than Newton's theory and which will give us food for reflection for many years to come.

Sir Oliver Lodge : We have heard a great discourse from the Master of Trinity and a master of physics. I unfortunately missed the beginning of the lecture, but I understand that Sir Joseph Thomson has been saying someting on the lines of his paper on the " Intermittence of Electric Force " which I have recently partly read in the *Proceedings of the Royal Society of Edinburgh*. All Sir Joseph's contributions earn our admiration, and I feel that a great deal will come of this curious admixture of the corpuscular and undulatory theories, and the chances of stray encounters. I myself do not feel that we have got to the bottom of it ; I do not know whether the lecturer does. I am not prepared to give in to the corpuscular theory yet, but certainly the quantum is a reality and introduces something odd which we must face. It is strange that we do not get radiation from a hydrogen atom, that the atom is stable ; but Sir Joseph seems to think that we might get radiation from a proton. Could it be from a pulsating proton ? I have been wanting the electron to pulsate like a hollow sphere under pressure. If it were to do so it might give these Millikan extra-high-frequency rays. The way in which an electron can be extruded by successive impacts of intermittency which operate during one part of its orbit—the elliptical orbit, not the spherical orbit—so that it accumulates energy until ultimately it expels it or is expelled, seems to me much in accord with what my brother and I worked out as the compound interest accumulation method, with occasional payment of a dividend, for expending radiation by quanta. Something is wanted to accumulate energy until it reaches a critical point, when the excess is paid off, and then it goes on to accumulate again at compound interest. The law of radiation says that there is that compound interest involved ; and I think that this intermittent probability impact theory is likely to give us a mechanism for it. It is noteworthy that Sir Joseph's work, combined with that of Prof. Whittaker of Edinburgh, is specially appropriate to a Kelvin Lecture, because it is trying to introduce more concrete ideas, and is a return to dynamics, so that the problems can be worked out on orthodox principles, with attempted explanation in terms of dynamics of those strange things which have crept into science during the 20th century and which none of us fully understand. Some have been inclined to say that the Newtonian dynamics was exploded by the new ideas and facts recently discovered. I think that Lord Kelvin would be horrified at that, and at the speculative character of modern physics, but admittedly their incorporation into dynamics is a matter of great difficulty. I think we have heard one of the steps towards the solution of that difficulty to-night. There are many interesting points in what Sir Joseph said about the avoidance of loss of energy and the formation of stationary waves by reflection. I am surprised that there can be reflection under free ether conditions, so that the waves do not go out beyond a certain distance and return without loss of energy, simply on dynamical principles, by reason of the period of the wave agreeing with the natural period of the ether oscillation at that place. If the ether has a natural period of oscillation it must have a fine-grained structure. Many things suggest that ; and I understand that that was one of Sir Joseph's contentions near the beginning of his lecture. I am not presuming to discuss a Kelvin Lecture, but am merely voicing our joint admiration for the brilliant pioneering work the lecturer has done and is still doing.

The vote of thanks was put to the meeting by the President, and was carried unanimously.

Sir Joseph Thomson briefly replied, and the meeting terminated at 7.15 p.m.

745TH ORDINARY MEETING, 29 APRIL, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 22nd April, 1926, were taken as read and were confirmed and signed.

A list of donations to the Benevolent Fund (see page 623) was taken as read, and the thanks of the meeting were accorded to the donors.

A paper by Messrs. B. S. Cohen, Member, A. J. Aldridge, Associate Member, and W. West, B.A., Student, entitled "The Frequency Characteristics of Telephone Systems and Audio-Frequency Apparatus, and their Measurement" (see page 1023), was read and discussed.

On the motion of the President a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 8.25 p.m.

54TH MEETING OF THE WIRELESS SECTION, 5 MAY, 1926.

Major B. Binyon, O.B.E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 14th April, 1926, were taken as read and were confirmed and signed.

A paper by Dr. R. L. Smith-Rose and Mr. R. H. Barfield, M.Sc., Associate Members, entitled "The Cause and Elimination of Night Errors in Radio Direction-finding" (see page 831), was read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.50 p.m.

54TH ANNUAL GENERAL MEETING, 27 MAY, 1926.

Mr. R. A. Chattock, President, took the chair at 6 p.m.

The notice convening the meeting was taken as read. The minutes of the Ordinary Meeting held on the 29th April, 1926, were also taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. J. O. Girdlestone and I. W. Chubb were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Member.

Lancaster, John Gill, M.Sc.

Associate Members.

Bass, Walter Alfred G., B.Sc.
Cargill, James Jamieson, B.Sc.
Fraser, John Charles W.
Greer, Henry James.
Hornbuckle, Thomas, B.Sc.(Eng.).
Howard, Atholl Charles.
Kemp, Leslie Charles, B.Sc.(Eng.).
Kerridge, Fred Bernard.
McLean, Neil.
Shklovsky, George Edward.
Thompson, Charles Barnard.
West, Robert Allen.
Williams, Harold Montague.
Winson, Victor Hautot, B.Sc.
Woodforde, Reginald Fielding M.
Woodward, Ernest Edward, B.Sc.

Graduates.

Barclay-Smith, Edward Alan, Capt. R.E.
Beynon, Benjamin Thomas.
Brown, Hugh (Jun.).
Clarke, John William.
Evans, Donald Wentworth.
Greenup, Luke Scott.
Hartley, Richard Kent.
Kempson, Ernest Ephraim.

Graduates—continued.

Lord, Will.
Love, Henry.
Petrie, John.
Phillips, Francis Eugene.
Pullein, John.
Ridley, John Harry D.
Staples, Alfred Silvester G.
Starr, Thomas Raymond.
Sutcliffe, William, M.Sc. Tech.
Walkland, Cyril Frederick.
Wallis, Albert Edward B.
Wayte, Frederick William.

Students.

Bacchus, George Rudolph.
Barnard, Howard Lucas, B.E.
Barry, Alfred George.
Borthwick, Roderick James S.
Bott, Francis Alfred N.
Browning, Jeffery Bellingham.
Buckle, Sidney William.
Chakravarty, Sailaja Nath, B.Sc.
Chalmers, George Herbert.
Chen, Yui Zong, B.Sc. (Eng.).
Diver, Frederick George.
Dunn, John Barrett J.
Eden, John.
Evans, Edward Stanley.
Ewart, Samuel John M.
Gainer, Harold.
Hare, Ronald George.
Hoult, Harold.
Jamieson, Douglas.
Kishan, Kewal.
Linsley, Brian.
McColl, Ronald John.
McKechnie, Alan Francis C.
Melville, John McIntyre.
Milne, Adam Robertson.
Moat, Eric Bert.
Nolan, Harold George B.
Osborne, Harry William.
Ozawa, John Hood.
Parsons, Ernest Ninnes.
Roberts, Geoffrey Nainby.
Robertson, Alexander.
Rogers, Frederic William.
Russell, Harold Frank.
Rutherfurd, William Gordon.
Salter, Charles.
Shuttleworth, John Irwin.
Singh, Kartar.
Smith, Harold Frank.
Swann, Samuel Arthur, B.Sc.(Eng.).
Topham, Robert Geoffrey.
Tucker, Joseph Harold L.
Uppal, Harnam Singh.
Venkate, Ailoor Subramanian.
Ward, Robert Taylor.
Watson, Alan Cairns.
Watt, James Leslie.
Wilde, Samuel Francis M.
Wilkinson, John Bevis.
Wilson, Richard Coleman.

Transfers.

Associate Member to Member.

Garland, James.
Harvey, Ronald John.
Heath, William George.
Hecht, Noel François S.
Mylan, William Francis M.
Phillips, Walter Charles S., B.Sc.
Roberts, John Ernest.
Sale, Harold Bernard.
Sanders, Harold Curtice.
Shackleton, John Milner.
Whitehorn, Harold Kenneth, B.Sc.
Yorke, Wilfred.

Graduate to Associate Member.

Andrew, Hugh Frederick, B.Sc.
Angus, Thomas Cochrane.
Coles, Carl Featherstone, B.Sc.
Dibben, Ernest, B.Sc.
Hadrill, Harold John.
Hardy, Alexander Edward.
Hodge, Thomas.
Marchand, Bernard, B.Sc.
Newman, Claude.
Rogers, Harold Belton, M.Eng.
Scott, Alexander Theodore.
Smithells, Thomas Archibald, B.Sc.(Eng.).
Thomas, David John.
Ward, Mark, B.Sc.(Eng.).
Weir, William.

Student to Associate Member.

Barfield, Robert Harry, M.Sc.(Eng.).
Elford, Ernest Norman.
Haigh, Harry.
Hubbard, Edward John E., B.A.
Huggins, Percy.
Taylor, Harold Edward.
Wallace, Milo Harrison.
Wardrop, Gilbert Glen.
Wilkinson, John Reed, B.Sc.Tech.

Student to Graduate.

Bloemsma, Jan.
Cannon, Hugh Stanley.
Horsley, William Douglas.
Imrie-Smith, William, B.Sc.
Jackson, John William.
Lancaster, Jack Kelvin.
Latimer, Walter Herbert.
Mann, Reginald William.
Marlowe, Thomas.
Russell, Douglas Arthur.
Shepherd, George Raymond, B.Sc.(Eng.).
Storrar, Jack Hector.
Valentine, Percy Williams.
White, Francis William.
Williams, Harold George.
Williams, John Dinwoody.
Wolfe, Standish Smyth.

The following lists of donations were taken as read and the thanks of the meeting were accorded to the donors:—

Benevolent Fund: (See list of Donations and Annual Subscriptions on page 720).

Library: G. L. Addenbrooke; Air Ministry; Allgemeine Elektricitäts Gesellschaft; C. M. R. Balbi; G. J. Burns; Prof. H. Bohle; O. Bonazzi; British Engineering Standards Association; H. J. Brocklehurst; Bureau Hydrographique International; Messrs. C. F. Casella & Co., Ltd.; Chief Inspector of Factories; Messrs. Constable & Co., Ltd.; Messrs. Crosby, Lockwood & Son; H. E. Dance; A. T. Dover; Messrs. Dunod; A. P. M. Fleming, C.B.E., M.Sc.; G. Giorgi; Mrs. Ayrton Gould; Messrs. C. Griffin & Co., Ltd.; G. M. Harvey; Hydro-Electric Power Commission of Ontario; Institute of Agricultural Engineering, Oxford; Institution of Railway Signal Engineers; R. O. Kapp; H. I. Lewenz; Messrs. Macdonald & Evans; W. C. Mountain; D. S. Munro; National Illumination Committee of Great Britain; National Research Council, New York; Messrs. S. Rentell & Co., Ltd.; Royal Technical College, Glasgow; Chief Experimental Officer, Signals Experimental Establishment, Woolwich; W. Hanneford Smith; Messrs. E. & F. N. Spon, Ltd.; Superheater Co., Ltd.; Syndics of the Cambridge University Press; Vereeniging van Directeuren van Electriciteitsbedrijven in Nederland; Weston Electrical Instrument Corporation.

The President, after summarizing the Annual Report of the Council (see page 655), moved "That the Annual Report of the Council for the year 1925–26 as presented be received and adopted."

Mr. E. W. Moss, in seconding the resolution, inquired whether the Council had considered the proposed Bill for the Registration of Engineers.

Mr. L. W. Phillips suggested that steps be taken with a view to members of the various electrical institutions in this country, America and the Continent, having the opportunity of purchasing at reduced rates the technical journals published by these institutions. He thought that the Faraday Medal should be made of gold or platinum instead of bronze, and also suggested that steps be taken with a view to membership of the Graduate class becoming a regular step in the ladder of Institution membership. He urged that steps be taken to delete the Bye-Law of the Institution regarding "enemy" membership.

Mr. F. W. Purse, after referring to the relatively small increase in Corporate Membership during the last two years, called attention to the fact that the average expenditure per member came out at £2 10s. per annum, so that Students paying £1 1s. subscription were far from bearing their share of the expenditure. He also urged some re-adjustment of the relative subscriptions of Members and Associate Members with a view to a larger number of the latter transferring to the former class.

Mr. A. H. Allen inquired whether the Council proposed to take any further steps in regard to the Electricity Bill before Parliament, beyond the letter which had been addressed to the Government.

The President, in reply, stated that, in view of the difference of opinion within the Institution in regard to the Bill, the Council had decided to take no further steps in regard to it. The Engineers' Registration Bill had been before the Council and the Council would take such action as appeared appropriate. Mr. Phillips's suggestions would receive consideration. As regards the Faraday Medal, bronze had been deliberately chosen by the Council after very careful consideration of all the circumstances. The Council had decided to alter the Bye-Law relating to enemy members, and this decision would be given effect to at the next revision of the Bye-Laws. In regard to Mr. Purse's criticism of the small increase in the number of Corporate Members, he thought that this was solely due to the stiffening up of the requirements. He was not, however, in favour of the Students' subscription being increased, as he thought they should receive every encouragement to become members of the Institution.

Mr. P. D. Tuckett (Hon. Treasurer) said: "I beg to move 'That the Statement of Accounts and the Balance Sheet for the year ended 31st December, 1925, as presented, be received and adopted.' I think I may say that the Accounts again disclose a healthy and prosperous position. The income has increased by a total of £1 459, and although it is true that the ex-

penditure has increased by nearly £5 000, we find, when we come to analyse it, that the increase is mainly attributable to one or two special items which were foreseen a year ago and are not likely to recur. The management expenses have increased by £981, the Institution building expenses by £2 055, and the *Journal* expenses by £1 087. Of the increased management expenses salaries and wages represent an increase of £569—an increase which reflects the increasing activities of the Institution and the growing seniority of the members of the staff. The £453 increase in the cost of printing is the other item of management expense showing a substantial increase, and it is accounted for by the biennial publication of the List of Members, so that a year hence there should be a corresponding reduction. Far the largest item in this year's expenditure as compared with previous years is the £3 786 for re-wiring the Institution building. It has proved a very costly expense, but it had to be incurred. Fortunately it is quite exceptional and I know of no liability of similar magnitude which we are likely to be called upon to face. Whilst dealing with the Institution Building expenses it may be of interest to note that the cost of heating shows a reduction of £184 as a result of the considerable sum which we spent the previous year in renewing the boilers. The increased cost of the *Journal* is largely due to some exceptionally long papers. There are various other small increases to which I need not particularly refer, but which I shall be glad to explain if any member desires further information about them. The net result for the year is that we are able to carry £2 000 to the Reserve Fund, as against £3 500 the previous year, and £1 196 to the General Fund as against £2 925 the previous year and £3 957 two years ago. The surplus for the year is thus substantially smaller than that shown during the two previous years, but I am glad to say that the subscriptions again show an increase of £471, and as long as this continues to be the case there can be little cause for anxiety as to our financial position. There is an increase in the income from investments of £372, and the Tothill-street property has brought us in £360 more than last year, thanks to a reduction of £375 in the cost of repairs and alterations. Turning to the Balance Sheet it will be seen that the mortgage on this building is reduced by £1 127, whilst the repair fund has been increased by £587 in consequence of our having incurred an expenditure of only £913 as against the annual contribution of £1 500 carried to the fund. The investments show an increase of £2 616 on the year, representing the invested surplus, and I am glad to say that their market value is practically the figure at which they stand in the Accounts, the depreciation being a negligible amount of less than 1 per cent. As set out in the Report, the assets amount to £145 336 against liabilities of £8 008, leaving a surplus of £137 328, an improvement of £4 312 on last year, so that the position is substantially strengthened, although the increase in the surplus is not as great as in the two previous years. So far as we can foresee, the expenditure of the current year should be less than that of the year under review, so that as long as the subscriptions continue to grow I think the members have every reason to feel satisfied with the financial position in which the Institution stands."

The resolution was seconded by **Mr. R. W. Paul.**

In reply to a question by **Mr. L. W. Phillips,** the Hon. Treasurer pointed out that the item of £235 11s. 6d. on the income side in respect of examinations was in no sense a profit; it was merely the difference between the fees and the expenses of printing and took no account of the incidental establishment charges, all of which were merged in the general expenditure of the Institution.

Mr. H. P. Girdlestone urged that the notices of meetings should be printed on one side only of the Meetings Card.

Mr. F. W. Purse inquired whether the Hon. Treasurer was entirely satisfied as to the financial position of the Institution in view of the fact that the total expenses, which in 1923 were £24 573, had amounted to £30 607 in 1925. He also urged the sale of the Tothill-street property.

The Hon. Treasurer, in reply, said that it was the intention of the Council to take advantage of the first opportunity of selling the Tothill-street property. In regard to the increase in expenditure, he pointed out that there had been in 1925 a non-recurring item of nearly £3 800 for the re-wiring of the Building. The Council had also been more liberal in grants made to such bodies as the British Engineering Standards Association and the Electrical Research Association and in the expenditure on lectures and papers, all of which had met with no disapproval whatever.

The resolution to receive and adopt the Accounts and Balance Sheet was then unanimously adopted.

The following resolution, moved by **Mr. F. W. Purse** and seconded by **Mr. Roger T. Smith,** was carried with acclamation: "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) The Hon. Secretaries of the Local Centres and the Local Hon. Secretaries abroad, and (*b*) The Hon. Treasurer (Mr. P. D. Tuckett)."

Mr. P. Rosling then moved: "That Messrs. Allen, Attfield & Co. be appointed Auditors for the year 1926–27." The resolution was seconded by **Mr. A. H. Allen** and carried unanimously.

The meeting terminated at 7.10 p.m.

55TH MEETING OF THE WIRELESS SECTION, 2 JUNE, 1926.

Major B. Binyon, O.B E., M.A., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 5th May, 1926, were taken as read and were confirmed and signed.

A paper by Mr. P. W. Willans, M.A., entitled "Low-Frequency Intervalve Transformers" (see page 1065), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 8.5 p.m.

INSTITUTION NOTES.

Scholarships.

The following Scholarships for 1926–1927 have been awarded by the Council :—

David Hughes Scholarships (value £50 each).

R. C. Mildner (University College, London).
W. S. Milner (Sheffield University).

Salomons Scholarships (value £50 each).

H. H. Fairhurst (Manchester College of Technology).
G. W. Lanyon (King's College, London).

Paul Scholarship (value £100).

R. G. Fuller.

Regulations for the Electrical Equipment of Buildings.

The Council have approved further alterations to the Eighth Edition of the above Regulations. Copies of the pamphlet containing the new alterations and those issued in July 1925 can be obtained from the Secretary for insertion in existing copies of the Regulations.

It is proposed to issue a revised (Ninth) Edition of the Regulations as early as possible next year.

Faraday Memorial Book Fund.

The Council have been asked by the Mayor of Southwark to draw the attention of members of the Institution to a project to commemorate Michael Faraday by forming a collection of standard current literature on electrical and allied sciences in the Central Reference Library of the Borough of Southwark, in which district Faraday was born.

It is proposed to form a Fund the income from which will be expended yearly in the acquisition of new books. Donations should be sent to The Mayor, Southwark Town Hall, Walworth Road, S.E. 17, from whom further particulars can be obtained.

Electric Storage Battery Locomotive Competition.

The Mines Department has recently issued the Report of the judges who were nominated, in connection with a prize of £1 000 offered by the late Mr. Charles Markham, to prepare a specification for, and to adjudicate upon, electric storage battery locomotives for use in British coal mines. One of the judges was Mr. Roger T. Smith, who was nominated by the Institution at the invitation of the Mines Department.

Ten British manufacturers submitted proposals for competition and the designs of five of these were selected as suitable for manufacture. Extensive trials were carried out, of which particulars are contained in the Report, and a general description is given of the successful type of locomotive. Copies of the Report can be obtained from H.M. Stationery Office, price 1s. 3d. net.

National Certificates and Diplomas in Electrical Engineering.

The following have been approved under the scheme drawn up by the Board of Education and the Institution :—

Approved for Ordinary Grade Certificates (Senior Part-time Course) :—

Goldsmiths' College.

Approved for Higher Grade Certificates (Advanced Part-time Course) :—

Widnes Municipal Technical School.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 August–25 October, 1926 :—

	£	s.	d.
Anderson, C. (Manchester)		5	0
Barker, N. H. (Manchester)		5	0
Brooks, R. (Sale)		5	0
Coward, A. C. (Swansea)		10	6
Craig, J. L. W. (Hatfield Peverel)		8	6
de Oliveira, A. C. (Rio de Janeiro)		5	0
Eccles, E. E. (London)	1	1	0
Farrar, M. (Twickenham)		5	0
Gandhi, K. C. (Lahore)		5	0*
Gomes, C. (Rio de Janeiro)		3	6
Graham, D. H. (Coventry)		5	0
Gregory, R. W. (Hexham)	1	7	6
Haley, W. E. (Shipley)		5	0
Heaney, J. W. (Birkenhead)		5	0
Hutton, J. C. (Birmingham)		15	0
Kempster, J. W. (Port Glasgow)	2	12	6
L., H. M. (London)	2	2	0
M'Dermid, P. (Glasgow)		5	0
Maquay, G. A. (Chicago)	1	0	0
Moller, O. P. (London)		5	0
Moscrip, W. R. (London)		5	0*
Palmer, W. G. (Sheffield)		10	6
Petrides, S. A. (Nicosia, Cyprus)		10	0
Pickersgill, A. (Cleckheaton)		15	0
Ridding, J. W. (South Farnborough, Hants)		3	6*
Smith, W. G. (Manchester)		10	6
Speirs, C. W. (London)	5	5	0
Stewart, C. (Rugby)		5	0
Traynier, M. A. (Montevideo)		8	6
Tremain, A. G. (Johore Bharu, F.M.S.)		15	0
Tyrrell, C. F. (Rangoon)	1	1	0
Weaver, Horace G. (Newport, Mon.)		5	0
Welbury, W. (Bridgend)		15	0
Whitehead, F. (London)		3	6
Williams, C. S. (Chippenham)		2	6*
Wood, L. E. (Bradford)		5	0

* Annual Subscriptions.

OBITUARY NOTICES.

HENRY FLEETWOOD ALBRIGHT was born at Lancaster, Pa., on the 5th October, 1868, and died on the 11th May, 1926. He was vice-president of the Western Electric Company, in charge of all its manufacturing plants in the United States, and also played a prominent part in the planning and organization not only of the plants of the Western Electric Co., Ltd., in England, but also of many of the telephone manufacturing plants in continental Europe. The biggest testimonial to his business genius is the well-designed Hawthorne Works of the Western Electric Co. He was educated at Philadelphia, Pa., and after a short time with the Thomson-Houston Co., as a sales engineer, he joined the Western Electric Co. in 1892. In 1894 he was transferred to the construction department at New York, his first work being the reconstruction of the power plant. The marked increase in efficiency of the plant won for him the position of factory engineer. One year later he was made assistant superintendent, and four years later, in 1899, he became superintendent of the New York factory. It was about this time that he began to group together under responsible heads departments which performed the same general functions. In 1905 the first buildings of the Hawthorne Works were erected and he personally supervised the drawing up of an ultimate factory lay-out, which has been consistently followed ever since. He also planned the lay-out for the factory now under construction at Kearny, N.J. In 1908 he became general superintendent of the company's manufacturing plant, when he moved to Chicago, and in 1917 he was elected a vice-president of the company. Throughout his career he was keenly appreciative of the human side of industry, realizing earlier than many the importance of sound employee relations. He joined the Institution in 1895 as a Foreign Member and was elected a Member in 1902.

DAIZABURO AWOKI, a member of the fifth class of the Imperial Japanese Order of the Sacred Treasure, died suddenly on the 13th September, 1924, at Tokio. He was born in 1859 in Chiba Province, and graduated in 1884 after taking the electrical engineering course of the Imperial Japanese College of Engineering. He at once obtained an appointment as an engineer in the Japanese Telegraph and Telephone Department, and subsequently served as postmaster at Kagoshima, Kobe, Kyoto and Yokohama. He retired in 1905 and later became a director of various companies. He was elected a Foreign Member of the Institution in 1888 and a Member in 1911. I. N.

COLONEL CHARLES FREDERICK COBBE BERESFORD, R.E., whose last appointment was Colonel on the Staff Chief Engineer in Ireland (1898–1902), was born in 1844, being the elder son of the late Rev. Charles Claudius Beresford, and great-grandson of the Rt. Hon. John Beresford, M.P., brother of the 1st Marquess of Waterford, and second son of the 1st Earl of Tyrone. He obtained his first commission in the Royal Engineers in 1865, and as a subaltern he was employed with the G.P.O. Telegraphs, and for 4 years with the Telegraph Troop of the Royal Engineers. He married in 1877 Edith Gertrude, daughter of Salisbury Baxendale, Esq., of Bonningtons, Ware. He was promoted Captain in 1878, and in 1879 passed for the Staff College, passing out in 1880. In 1881, Captain Beresford served with the Expeditionary Force in the Transvaal, being present at several of the actions, and rendering excellent service with the field telegraphs and signalling. On his return to England, he was posted to the Intelligence Branch in the War Office, but in 1883 he returned again to the Postal Telegraphs. In 1885 he was sent as Director of Telegraphs with the Sudan Expeditionary Force, to Suakin, for which service he received the medal and clasp and bronze star. After the campaign was over, being promoted to Major's rank, he was given command of the 2nd Division of the Telegraph Battalion, employed with the Postal Telegraphs, holding that appointment for four years. In 1889 he was selected for the command of the 1st Division of the Telegraph Battalion at Aldershot, commanding it until he was promoted Lieut.-Colonel in 1892. His later services were with the general duties of his corps. He was promoted Colonel in 1898. He was an ardent advocate of telegraph services in the Army, and was largely responsible for the progress made, furthering with all his power the alliance between Civil and Military Telegraphs. He contributed many papers to the *Journal* of the R.E. Institution, on the use of telegraphs and telephones in the field, as well as on the collection and transmission of intelligence in war. He was placed on retired pay on account of age in 1902, and died at Camberley, where he resided, on the 13th December, 1925. He joined the Institution as a Member in 1877 and served on the Council in 1887–88. He also served as Vice-Chairman of the Dublin Local Section Committee in 1900. F. G. B.

JAMES THOMSON BOTTOMLEY, M.A., D.Sc., LL.D., F.R.S., who died in Glasgow on the 18th May, 1926, was born in Belfast on the 10th January, 1845. His father was William Bottomley, a J.P. of Belfast,

and his mother a sister of the late Lord Kelvin. He was educated at Queen's College, Belfast, and Trinity College, Dublin, where he had a distinguished career and was gold medallist when he took the degrees of B.A. and M.A. He started his scientific career by becoming assistant to Prof. Andrews at Belfast, afterwards becoming a demonstrator of chemistry and physics in King's College, London, and in 1870 he came to Glasgow University to act as Arnott and Thomson demonstrator in the Department of Natural Philosophy, at the head of which was his uncle, Sir William Thomson. He held this position until 1899 when Lord Kelvin resigned from his professorship. During these 29 years Dr. Bottomley was continuously engaged in research work and his researches covered a very extensive field, including liquefaction of gases, the use of liquid air for experiments on radiation at very low temperatures, the air thermometer, the bolometer, emissivity and conductivity of wires in vacuum, radiation from bright and black bodies, vacuum pumps, thermocouples, modulus of elasticity, and the electrical properties of platinoid, etc. These papers were contributed mostly to the *Proceedings of the Royal Society* and the British Association Reports. He published a book on Theoretical Mechanics, in two parts: Vol. I, Dynamics; Vol II, Hydrostatics. But as an author he is best known for his "Four-Figure Mathematical Tables: comprising logarithmic and trigonometrical tables, and tables of squares, square roots, and reciprocals." As time went on Sir William Thomson delegated to Mr. Bottomley a good deal of the lecturing to students. He belonged to a type not uncommon in our universities, of distinguished scholars and amiable gentlemen, enthusiastic in their own department of study, and with every good desire in the world to help their students, but largely unable to impart their knowledge in the class room. Uncle and nephew were both deficient in this respect, the one in being too advanced and abstruse for the average student, the other in being too ridiculously simple. He elaborated the obvious, sometimes painfully, though unconsciously, wasting time striving to elucidate minor points which all understood. He did not seem able to state the salient points and pass on. As consulting engineer Dr. Bottomley acted for the Scottish Asylums Board and for Nobels, Ltd. He had a regular electrical engineering consulting practice, mostly concerned with lighting installations, such as Skibo Castle, Roxburgh Castle, etc. Dr. Bottomley became associated with the business of Kelvin, Bottomley and Baird, when the firm was floated as a private limited company in 1900, and on the death of Lord Kelvin in 1907 he was appointed chairman, a position which he continued to fill until his death. In recognition of his distinction as a scientist and of his long and honourable connection with the Glasgow University the degree of Doctor of Laws was conferred upon him in November 1904. He was elected an Associate of the Institution in 1872 and a Member in 1889. He was a Member of Council in 1873 and in 1910 served on the Committee of the Glasgow Local Section, now the Scottish Centre. M. M.

HENRY WHITE BOWDEN commenced his electrical career at Wolverhampton, where he was articled as a pupil with Messrs. Elwell Parker and Co. For two years he was electrical engineer to the Eastbourne Electric Light Co. In 1891 he took up the position of general manager to the House-to-House Electric Light Co. at Kensington (now the Brompton and Kensington Electricity Supply Co.). He was prominently connected with that company's affairs for many years, and during this period of continuous extension also became a director of the old Blackheath and Greenwich Electric Light Co. (now the South Metropolitan Electric Light and Power Co., Ltd.) in 1898 and supervised the erection of much of the plant of the South Metropolitan Co., of which he was managing director and engineer-in-chief. In 1906 he also joined the Board of the Woking Electric Supply Co. He was one of the pioneers of electricity supply in London, and in these days, when so much is being done to bring electrical service within the compass of the general populace, it is interesting to recall that he was very early in the field with free-wiring installation arrangements which gave the consumer up to six points free of charge. He resigned his position as engineer-in-chief of the South Metropolitan Co. in 1919, also his seat on the board, but he continued as consulting engineer to the company. He died in May, 1926, at the age of 58. He was elected an Associate of the Institution in 1889 and a Member in 1904.

J. H. B.

EDWARD EUGENE BROWN, born in the early sixties, died peacefully in his sleep at his home in Brighton on the 19th March, 1926, after much suffering from heart trouble. He was educated at Denmark Hill Grammar School and at the Birkbeck Institution, and, later, at Finsbury Technical College and at the Durham College of Science. He was originally intended for the medical profession, and spent a year in his uncle's surgery at Haverfordwest, Pembrokeshire; but his own desire was always for engineering, and he eventually turned to that as a career. After being in several workshops in London and in Cardiff, and after some further experience in Sunderland, he went in 1885 to the works of Messrs J. H. Holmes and Co. in Newcastle-on-Tyne, where he remained for 21 years, beginning as a draughtsman, and afterwards becoming chief designer. He was associated with Mr. J. H. Holmes in the design of the dynamos used to supply current to the electric lamps at the 1887 Newcastle Exhibition, and of some early train-lighting sets made for the late Mr. Langdon of the (then) Midland Railway Co. in 1889. After he left Newcastle in 1906, he spent some years in Bath with the Griffin Engineering Co., Ltd., makers of internal-combustion engines and gas producers; and he was subsequently with the Braulik Engineering Co. in London. About the beginning of the 1914–18 war he joined the Sperry Gyroscope Co., Ltd., and worked in their drafting and design department until 1916, when he went to the Steel Wing Co., Ltd., of Hither Green, manufacturers of all-metal aeroplanes of the corrugated strip type. The first metal B.E.2.D. wings were built to his designs in 1917, and the tests of these gave the necessary data for the development of the company's special method of construction, with the early stages of which he was thus associated.

Although he was compelled by ill-health to give up much of his work, he continued to be in touch with the Steel Wing Co. about their patents until his death. He appears to have had other minor engineering interests, but what has been written indicates the main course of his life's work. Of Welsh origin, he was intensely musical and artistic in his temperament, and had some skill both as a painter and as a violinist. He was, in addition, a man of wide reading, and one who travelled much in Europe. To his associates his generous sympathies made him always kind, and he was most willing to help young people during their training time in every way within his power. As one who knew him perhaps better than most people says of him, "on the human side he was genial, modest, good-humoured and a loyal friend." So he obtained the worthy regard of his colleagues by his personal character as well as by his knowledge and his ability; and he has the reward of a full and active life. He joined the Institution as an Associate in 1890, and became a Member in 1891. He was amongst those who went to Switzerland with the Institution in 1901, and he was Chairman of the Newcastle Local Section (now the North-Eastern Centre) of the Institution during the Session 1904–5. T. C.

CECIL LEONARD CARTWRIGHT was born at Braintree, Essex, in 1877. He completed his education at King's College, London, and then went for some years to the Westinghouse Co. in Pittsburgh, U.S.A. In 1907 he was appointed Professor of Mechanical Engineering at the College of Engineering, Guindy, Madras. In 1920–21 he served as Acting Principal of the College, and was appointed Principal in 1922. He died at Great Bardfield, Essex, on the 18th April, 1926. He joined the Institution as an Associate Member in 1912 and became a Member in 1914.

CONRAD WILLIAM COOKE died at Hampstead on the 9th January, 1926, in his 83rd year. By his death the Institution loses one of its oldest members. He was well known to all who were connected in any way with the early days of electrical work. Born in 1843, the son of an eminent artist, he was trained in the establishment of Messrs. J. Penn and Son, the well-known engineers of Greenwich. He began professional work as a civil engineer by surveying and laying out the first Isle of Wight railway under Sir Charles Fox. Afterwards he became assistant to Sir Joseph Whitworth. His connection with electrical work seems to have begun at the time of the invention of the Gramme dynamo in 1870. This greatly attracted him. He recognized that it made direct-current dynamo-electric generation practicable, for it gave a current not merely continuous in direction but also sensibly uniform in strength. It is said that the patent specification of this invention was brought out of Paris by balloon during the siege by the Germans in 1870. Cooke recognized its importance and introduced and made the machine here. He used it to supply a searchlight on the clock-tower of the Houses of Parliament, all the work being designed and carried out by him. He joined the Institution's predecessor, the Society of Telegraph Engineers, as an Associate, in 1875, and became a Member in 1878. He remained a Member and maintained his interest in electricity all his life, but his activities were not confined to that branch of engineering. He experimented on improvements in gas lighting, took part in the introduction of the incandescent gas lamp here, and became consulting engineer to the Welsbach Co. He was led to take a great interest in the telephone by being present when Kelvin first described Bell's invention—at the British Association meeting in 1876. He then wrote the oft-quoted article on this invention which appeared in *Engineering*. In 1879, in a lecture at the Society of Arts, he first showed the loud-speaking receiver of Edison. He was the author of the two portly volumes on "Electric Illumination," which were published in 1882 and 1885 by *Engineering*. They are still useful as books of reference as to early applications. He wrote a memoir of Gilbert, of Colchester, and with Prof. Silvanus Thompson founded the Gilbert Club to produce the handsome translation, by P. F. Mottelay, of Gilbert's "De Magnete" (1893). He was interested in astronomy and was chosen to take part in the Solar Eclipse Expeditions of 1896, 1900 and 1905. His general engineering knowledge made him a valued member of the juries of many exhibitions, including the Chicago Exhibition of 1893. He was of a very happy disposition—this, and his broad views, great experience and erudition, made him a general favourite in the engineering world, and he was able to enjoy life to a mature age. He had five sons and a daughter by his first wife. These all survive him, as does his second wife, Miss Sophie Augusta Bonnavie, daughter of a Christiania advocate. He presented to the Institution library a very interesting and admirable collection of drawings made by his father, E. W. Cooke, R.A., F.R.S., the marine painter, of scenes on H.M.S. "Agamemnon" during the laying of the first Atlantic cable in 1857 and 1858. In an accompanying letter he mentioned that his father was the only Royal Academician who was also a Fellow of the Royal Society. This collection, which also contains some excellent photographs taken on this cable ship, cannot fail to be of interest to old telegraph men. W. M. M.

WILLIAM RANSON COOPER, M.A., B.Sc., was born in 1868, at Hampstead, and died on the 15th March, 1926. He graduated in the Royal University of Ireland as Master of Arts in Mathematical Science in 1890, afterwards going to the Central Technical College, where he studied for three years. Gaining a works premium there, he went to the Richmond Electricity Supply station, and to Messrs. Latimer, Clark, Muirhead and Co., who were then manufacturing dynamos and other electrical plant. He next went to King's College and took his B.Sc., London, in physics and chemistry. In 1895, Mr. G. H. Baillie and he joined Mr. J. Swinburne as assistants, becoming partners soon after. Mr. Swinburne had started *Science Abstracts*, and was editor at first. Mr. Cooper took over the editorship with its rapidly growing responsibilities; and its subsequent success is largely due to the good work he did in those days. During his partnership he did a great deal of difficult work. At one time he would be

analysing the rare earths used in gas mantles; at another, he was putting in sewage plant and refuse destructors. Not only had he a good knowledge of general engineering, but he was also a good chemist and an able electrician, with a good mathematical foundation. His chief characteristic from a technical point of view was accuracy and thoroughness. All his work could be relied upon absolutely. It was always done, and always done correctly. While in partnership with Mr. Swinburne he became editor of the *Electrician*. As this gradually absorbed his whole time his partnership was dissolved, but not the friendship which went with it. He was secretary and director of the Damard Lacquer Co., makers of phenol formaldehyde resin products; and the success of that company is largely due to his strenuous work in its development. He wrote a valuable work on "Primary Batteries," and edited the present edition of the *Electrician* primers. He also revised W. G. McMillan's "Electro-Metallurgy." He contributed various papers to scientific societies and the technical Press. In 1902 he was awarded a Telford Premium by the Institution of Civil Engineers for a paper on "Electric Traction." He was also interested in automobile matters, and carried out investigations on the problem of dust prevention. He served on the Council of the Institution of Electrical Engineers (1900–3), and of the Faraday Society. He was also vice-president of the Physical Society, and was honorary secretary for many years. He was always a modest man, in spite of his ability; and he was always fair and pleasant to deal with. If he had a temper, there was no evidence of its existence. He had a cultivated mind, was well-informed outside his profession, and was musical. He was elected an Associate of the Institution in 1895, an Associate Member in 1899, and a Member in 1903. J. S.

GEORGE STEPHEN CORLETT, who died at Wigan on the 28th March, 1926, at the age of 59, after residing in that town for nearly 40 years, was born at Andreas, Isle of Man, where for many years his father was a member of the Manx House of Keys. He received his education at King William College, Casteltown, Isle of Man, and served his apprenticeship with an electrical engineering firm in Cardiff. After a short time in Newcastle-on-Tyne he went to Wigan and founded the Corlett Electrical Engineering Co. In 1914 he severed his connection with the company and set up as a consulting engineer, specializing in the applications of electricity to mining, and in that connection his advice was widely sought. He was elected a Member of the Institution in 1911.

GEORGE HENRY COTTAM was born in 1850 and died on the 1st April, 1926, at his home in Coulsdon, Surrey. He was a son of the late Beaumont Cottam of Walsall and was educated at the Grammar School there and afterwards at Neuwied, Germany. He was apprenticed to Messrs. Wm. Foster and Co. of Lincoln for 5 years, and after some 16 years' experience in general engineering he took up the electrical side in 1882. Subsequently he worked for the Faure Electric Accumulator Co. and the Anglo-Austrian Brush Co. and superintended the erection of electrical undertakings in Hungary. Electric light and traction work in Spain was followed by an appointment at the Bankside generating station of the City of London Electric Lighting Co., Ltd., on behalf of the Brush Co., the contractors. In 1893 he superintended the erection of the electricity works at Hanley and afterwards took up the position of electrical engineer to that municipality. In 1895, following the resignation of Mr. Chattock, he was appointed chief electrical engineer to the Hampstead Vestry, afterwards the Hampstead Borough Council, which appointment he resigned in 1912, afterwards being retained as consulting engineer up to the time of his death. He was hon. treasurer of the Incorporated Municipal Electrical Association from 1896 to 1900. He was elected an Associate of the Institution in 1892 and a Member in 1895. L. M. C.

WALTER DIXON, who died on the 12th July, 1926, was born in Hull in 1861, and was educated in that city. He commenced his engineering career with Messrs. Amos and Smith, Ltd., engineers, Hull, with whom he remained for about 10 years. On leaving he joined the firm of Messrs. Richard Hornby and Sons, Ltd., Grantham, for whom he supervised some important contracts in London, Ireland and other places. In 1891 he went to Glasgow to join Mr. M. B. Mountain, who represented the firm of Messrs. Ernest Scott and Mountain, Ltd., Newcastle, the Priestman oil engines and other interests. He afterwards founded the firm of Walter Dixon and Co. electrical contractors, Glasgow, and carried out many important iron and steel works electrification schemes. At this stage also he was connected with the late Mr. James Riley in the early development of the gas engine for iron and steel works, and he was also among the pioneers in the introduction of three-phase alternating current to iron and steel and allied works. About 1903 Mr. Dixon gave up his contracting practice, and the firm's energies were devoted to consulting work. Among some of his achievements in this connection may be mentioned the complete electrification of the properties of the Ebbw Vale Steel, Iron and Coal Co., Ltd., with which he was connected for over 20 years, during which period the scheme grew from quite small dimensions to an installation consisting of three or four large power stations, with a total equipment of over 30 000 kW. He was also responsible for the electrical equipment of the Rothesay Dock, belonging to the trustees of the Clyde Navigation, which was the first dock in this country to be electrified completely, and embodied many features which had not previously been undertaken in any part of the world. Mr. Dixon's interests were varied, and, apart from his business, he was actively interested in numerous learned societies to which he contributed many papers. He was a Past-President of the West of Scotland Iron and Steel Institute, and at the time of his death was President of the Glasgow and West of Scotland Branch of the Institution of Mechanical Engineers. He was elected a Member of the Institution of Electrical Engineers in 1898. F. A.

GEORGE RICHARD DRUMMOND was born in 1876. His general education was obtained at the Roan

School (Greenwich), Margate College, and King's College. He received his technical training from 1895 to 1900 with Messrs. Siemens Brothers, of Woolwich, and during the same period attended night classes at Finsbury Technical College. While with Messrs. Siemens he passed through the instrument shops, cable-testing room, dynamo department and calibrating and testing room. For a short time before he left Messrs. Siemens he was in charge of their lighting and power station. In 1900 he went as senior charge engineer to the Leyton and Leytonstone electricity works, where he remained for two years. In 1903 he went to India as the electrical engineer to the Bombay, Baroda and Central India Railway, for whom he put down and ran two d.c. central stations. From 1904 to 1913 he occupied the position of electrical and mechanical engineer to Bikaner State. During this period he prepared and installed a three-phase h.t. lighting and power transmission scheme, including five substations. He also installed a complete telephone scheme for Bikaner capital. He had complete charge of the Bikaner waterworks, including four complete pumping stations, two being electric and two steam. In 1908 he was appointed by the Maharajah of Gwalior consulting engineer to Gwalior State, for whom he prepared a three-phase h.t. transmission scheme with substations. He later went to the State of Jodhpur, where he designed and installed a new power house and equipment on modern lines. In 1916 he was appointed chief electrical engineer to the Lahore Electric Supply Co., where he remained for some years. During that time he drew up designs for the complete reorganization of the Lahore Company's system, and although the war and financial difficulties prevented Mr. Drummond himself from carrying out the work he had designed, it has been done since by others. During the period 1916–1921 he also acted as consulting engineer to the Jullundur Electrical Syndicate and the Sialkote Electrical Syndicate. He left Lahore in 1921 and, after some years' absence from the North of India, returned in 1925 to take up the position of electrical engineer to the Amritsar municipality, for whom he was engaged at the time of his death in drawing up designs for the extension of their plant and system. He was never a purely station engineer, and found himself unable to remain in any position which merely required administrative duties from day to day. He was full of energy and was always looking for an outlet for this in positions where new works or reorganization were required. During his life in Northern India he acted as consultant on many occasions for Indian States and others requiring technical help and advice. After so many years of energetic life on the plains of India, in climates and under conditions trying to even the strongest, he found another hot season on the Punjab plains too trying for him. He died at Rawal Pindi from heat stroke on the 12th July, 1926, while on his way to the hills to recuperate. C. C. T. E.

ANDREW GRAY, M.A., LL.D., F.R.S., was born at Lochgelly, Fifeshire, on the 2nd July, 1847, and died in Glasgow on the 10th October, 1925, in his seventy-ninth year. In his native village school he was well grounded in arithmetic and practical mathematics, including surveying, and shortly after leaving school he came, in Edinburgh, under the influence of James Pryde, the editor of "Chambers's Mathematical Tables" in the old Watt Institution. He matriculated in the University of Glasgow in 1872 and graduated M.A. with honours in Mathematics and Natural Philosophy in 1876, became private secretary to Sir William Thomson (afterwards Lord Kelvin), and in 1880 was promoted to be chief official assistant. On the foundation of the University College of Wales at Bangor in 1884 he became its first Professor of Physics. In 1899 he was appointed Professor of Natural Philosophy in the University of Glasgow, to succeed Lord Kelvin, a post which he held until 1923, when through ill health he was forced to resign. In 1884 he published "The Measurement of Electric Currents and Potentials in Absolute Measure." Then between 1888 and 1893 he issued "The Theory and Practice of Absolute Measurements in Electricity and Magnetism," in three volumes. In 1921 appeared a revised edition in one volume of 837 pages. It is an enduring testimonial to the industry, as well as to the powerful and wide grip of electrical and magnetic measurement possessed by him. In 1898 appeared a "Treatise on Magnetism and Electricity." In 1896 he received from his Alma Mater, the University of Glasgow, the degree of LL.D. and was made a Fellow of the Royal Society of London. Prof. Gray first joined the Institution as a Member in 1900. He resigned his membership in 1905 and rejoined the Institution in 1912. In 1914 he delivered the Kelvin Lecture, taking as his subject Lord Kelvin's work on gyrostatics. The lecture was illustrated by means of the original Kelvin tops, which were taken from Glasgow to London and shown in action. In 1919 appeared the monumental "Gyrostatics and Rotational Motion," the fullest treatment of the subject in any language: it stands alone among books treating of the properties of rotating bodies. Prof. Gray's knowledge of the equations involved, it is stated, latterly became almost intuitive. M. M.

ANDRÉ HILLAIRET, head of the Hillairet works at Paris, was born on the 6th September, 1857, and died on the 23rd February, 1926. He completed his education at the Lycée d'Angoulême and subsequently at the Lycée St. Louis, Paris. From 1877 to 1880 he studied at the Ecole Centrale des Arts et Manufactures and obtained its engineering diploma. He at once turned his attention to the electrical industry, the future importance of which was evident from the Paris Exhibition of 1881. In 1880 he became manager of the Breguet works, and in 1885 founded the Hillairet-Huguet works, which soon became well known for their dynamos and motors, particularly in connection with electric capstans for hauling wagons on rails. In 1884 he published an important book on the subject of electric transmission. In 1890 he carried out at Domenes the first high-tension traction installation in France, and in 1894 improvised in a few days an electric traction installation at the Béraudière mines. He was on the governing body of the Ecole Centrale, a member of the Electricity Committee of the Ministry of Public Works, a member of the French Electrotechnical Committee, president of the Societé Française

des Electriciens in 1901, and president of the Societé des Ingenieurs Civils de France in 1906. In these societies he held a prominent position owing to his ability and his unfailing memory which enabled him to recall on any occasion stories and incidents forgotten by most of his colleagues. By his death electrical engineers in France have suffered a great loss. He joined the Institution in 1897 as a Foreign Member, and became a Member in 1911. J. G.

FRANCIS HIRD, B.A., managing director of Siemens Brothers and Co. died on the 25th March, 1926, in his 59th year. He was born in 1867, the second son of William Hird of Darlington, and was educated at the Bradford Grammar School and at Trinity College, Cambridge, where he obtained a Natural Sciences Exhibition. At Cambridge he devoted his attention to natural science, specializing in physics, and took a First Class in the Natural Science Tripos in 1887 at the unusually early age of 19. Two years later he joined the staff of Messrs. Siemens Brothers and Co., with which firm the whole of his professional and business life was destined to be spent. In the earlier years of his connection with Siemens Brothers, Mr. Hird's attention was given chiefly to the technical side, and after three or four years' service he became chief dynamo designer to that company. In September 1902 he was appointed chief engineer of the electric light and power department, and took a prominent part in forwarding the many important developments in electric lighting and power transmission which were taking place at that time. Amongst these may be mentioned the original equipment of the Waterloo and City Railway; a considerable portion of this was designed and constructed by Messrs. Siemens Brothers, and Mr. Hird took a keen personal interest in this contract and was responsible for many of the special features introduced in this, one of the earliest of the London "tube" railways. When the dynamo works of Messrs. Siemens were removed from Woolwich to Stafford, Mr. Hird was acting as consulting engineer to the electric light and power department, and in that capacity was a frequent visitor to Stafford, although his headquarters were in London at York Mansions, and until 1904 when he was appointed manager of the Stafford Dynamo Works and took up a permanent residence at Stafford. This may be said to have been the turning point in his career, when it became necessary for him to devote more and more of his time to the administrative rather than the technical side of the business, and although the position he attained shows his great abilities in both administrative and commercial lines, he often used to deplore the fact that he could not devote more time to keeping up with the newer developments of science in its technical applications. In spite of these limitations his scientific and technical knowledge was of no mean quality, and his knack of getting as it were intuitively at the gist of the argument enabled him to advise his staff on any difficult technical problems, especially on new development work, and he was always ready to assist his departmental chiefs in any technical difficulty. When Siemens Brothers decided on the policy of reorganizing the apparatus department at Woolwich on the lines of modern mass production, Mr. Hird was asked to return to Woolwich and take charge of the new organization. In 1908 he was given charge of both the manufacturing and commercial sides of the apparatus department. In this capacity he had the opportunity of putting to work some of the first automatic telephone exchanges opened in this country. In June 1922 he was appointed general manager of Siemens Brothers and Co., and in April 1925 managing director of the company. On the 1st February, 1926, less than a year after this last appointment which crowned his career, he was taken ill whilst in the chair at a conference with his chief officials, and although his illness was not at first considered serious he never rallied, but gradually grew weaker. During his 37 years' service with Siemens Brothers he saw and took part in nearly all the immense developments of the electrical industry which have taken place during the period; first in heavier engineering works, dynamo and central station design, and latterly in telephone and wireless work. Highly respected by his colleagues, he will be remembered by them and by the many leaders of the electrical industry with whom he came in personal contact, as a man of great technical and commercial abilities with a very quick grasp of any new problem, possessed of a strict sense of duty and devotion to the interests of the firm with which he was identified, and of invariable kindliness to all with whom he came in contact. All who knew him personally will feel that not only his firm but the whole electrical industry is the poorer from his untimely death. He was elected a Member of the Institution in 1903, and although the calls on his time did not allow of his taking a prominent part in its affairs, he always had its interests at heart. In 1906, while at Stafford, he served on the Committee of the Birmingham Local Section, now the South Midland Centre. W. B. H.

HARRY HOLLIDAY was born in Melbourne in 1887, elder son of the late Mr. T. Bradley Holliday, a well-known engineer in that country. After spending a short time with Messrs. Dick Kerr and Co. on tramway construction, he was appointed in 1906 assistant to the general manager of the Hastings Tramways Co., Ltd. A year later he became engineer and manager to the Torquay Tramways Co., Ltd., a position which he filled until 1914, when he was appointed engineer and manager to the Rhondda Tramways Co., Ltd. This position he held until his death, which took place on the 12th June, 1926, as the result of a chill contracted on returning from Switzerland, where he had been for the previous six months owing to a breakdown in health. He was elected an Associate Member of the Institution in 1912 and a Member in 1918.

I. L. W. V. JENSEN was born on the 8th May, 1859, and died on the 5th March, 1925. He was for many years the chief engineer of the Copenhagen Telephone Co., which he joined in 1882. A man of brilliant parts and exceptional learning acquired by unremitting energy, he quickly rose to a leading position in technical matters. His insight into mathematical physics and his extensive knowledge of materials and their properties, rendered him an undisputed authority

on everything appertaining to the construction of apparatus. In respect of electrotechnics and mechanics he was most exacting, his maxim being that the best is not too good. Dr. Jensen's mathematical gifts won him the highest esteem of mathematicians both at home and abroad, and if he had not devoted himself by preference to telephony he might have made a great name in mathematical history. He was the recipient of many scientific honours. President of the Mathematical Association, member of the Scientific Society and of various Danish and foreign learned bodies, vice-president of the Danish Electrotechnical Committee, he was Dr. Phil. *honoris causa* of Lund University. For many years a sufferer from ill-health, he was compelled in 1924 to retire from active work. His name will be associated for all time with the development of technical science in connection with the Copenhagen Telephone Co. He was elected a Foreign Member of the Institution in 1887 and a Member in 1911. From 1899 until his death he acted as Local Honorary Secretary and Treasurer for Denmark.

ANDREAS PETER LUNDBERG, who died on the 22nd February, 1926, was born on the 7th March, 1831, at Bjorneborg's Bruk, Wermland, Sweden. He was apprenticed to a mathematical instrument maker in Stockholm. At the end of his apprenticeship, King Oscar I of Sweden personally secured for him a premium from the Government to enable him to visit foreign countries and so extend his experience. This followed the making of some special nautical instruments which were presented to the Crown Prince (afterwards Oscar II of Sweden) by some of his brother officers in the Navy. The Society of Arts and Trades in Stockholm, as a tribute to the excellent workmanship then displayed, presented Mr. Lundberg with its diploma and silver medal. He was the maker of the intricate Scheutz calculating machine, which was put into use in Somerset House and in the United States, after being shown at the Paris Exhibition of 1855. Subsequently he was employed by various mechanical firms in France, Germany, Denmark, Sweden, Russia, etc., and also as an engineer in the Russian Navy. In 1862 he visited England, where he became a naturalized British subject and remained until his death. He was employed, either as workman or foreman, by Messrs. Thomas Cooke and Sons of York, by Mr. John Browning, and by Messrs. Troughton and Simms. Later, he joined Messrs. Siemens Brothers, and while with that firm acted as foreman of the cable shop and also as assistant engineer on board the original C.S. "Faraday," when the first section of the direct United States cable was laid in 1874. After a venture in business on his own account in Bayswater, he was engaged in 1879 by Colonel R. E. Crompton, C.B., who was just then entering the profession. Mr. Lundberg was always proud of the fact that he was Col. Crompton's first man at Chelmsford, where he assisted in the development of the early types of Crompton arc lamps, etc. He also acted as this firm's representative at the first great Electrical Exhibition, which was held in Paris in 1880 and 1881. In 1882 he founded the firm of A. P. Lundberg and Sons and invented and manufactured the numerous requirements which became necessary as lighting by electric glow lamps developed, such as switches, plug connectors, lampholders and kindred apparatus. His firm also developed an examination scheme in electric switching, installation work, etc. This scheme brought home to many, who had previously given no thought to it, the possibilities of the subject. He joined the Institution in 1894 as an Associate, and became a Member in 1898.

SIR HENRY CHRISTOPHER MANCE, C.I.E., LL.D., who died at Oxford on the 21st April, 1926, was born in 1840. Educated privately, he joined the Persian Gulf Telegraph Department in 1863, and was employed on the laying of the first Persian Gulf submarine cable. Although one of the youngest of the expedition, he was selected for early promotion, and in 1879 was appointed electrician to the Department, which position he held until his retirement in 1885. He was the author of "Mance's method" for testing the internal resistances of batteries, communicated to the Royal Society in 1871 by Lord Kelvin, then Sir William Thomson; also the author of "Mance's method" for eliminating the effects of polarization and earth currents when testing cables having partial earth faults; this led to important economies in cable repairs. He further communicated various papers published in the *Proceedings* of the Society of Telegraph Engineers, on "A Method of Duplex Working," "The Respective Merits and Durability of Gutta Percha and India-rubber Joints," and "The Relative Susceptibility of Gutta Percha and India-rubber to Attacks from the Teredo." He also designed a "system of automatic translation suitable for unstable relays," which system was adopted in connection with the Persian Gulf cables. He was the first to publish a description of the remarkable light-circles phenomenon seen at rare intervals in the vicinity of the Persian Gulf, the light circles passing over the surface of the sea at the rate of 100 miles an hour. Mance's most noteworthy contribution to scientific development was the invention of the heliograph in 1869 at the age of 29. By a curious coincidence the idea first occurred to him on the coast of Baluchistan, where, over 2 000 years before, Alexander the Great had signalled to his armies from the neighbouring hills by means of the sun's rays reflected from his shield. As has occurred before, the Government were slow to realize the value of the new invention, and it was thanks to the initiative of Mance, who sent a number of his instruments to Lord Roberts for use during the second Afghan War, that the practical value of the invention was strikingly demonstrated, with the result that it has since been adopted in every military service, and has incidentally been made famous by Kipling in one of his "Departmental Ditties." Sir Henry Mance joined the Society of Telegraph Engineers as an Associate in 1873, and became a Member in 1877. He was a Member of Council in 1890, a Vice-President from 1892 to 1896, and President of the Institution of Electrical Engineers in 1897. He was also a member of the Institution of Civil Engineers and the Physical Society. After his retirement from the service of the Indian Government, Sir Henry continued to interest himself in electrical subjects. He was chairman of the Oxford Electric Co. from its foundation. He was

on the Boards of the Electric Construction Co., Davis and Timmins, Ltd., and the West African Telegraph Co., and a member of the Provincial Electric Supply Committee of the United Kingdom. Sir Henry was fond of sport of all kinds, a good shot, a lover of music, with a good voice, and a reciter of no mean order, and possessed a fund of personal experiences which made him a never-failing source of interest to his friends. Endowed with an essentially human and sympathetic disposition, he never spared himself to help a friend in need. He was practically blind for the last 10 years of his life. Undaunted, he stuck to his work and kept himself in touch with developments in spite of the effort of memory needed. He learned to read Braille after the age of 70. He was created C.I.E. in 1883 and Knight Bachelor in 1885, and was awarded the degree of Hon. LL.D., Aberdeen, in 1903. He married in 1874, and leaves a widow, three sons and two daughters.

H. O. M.

JOHN MACINTOSH MACKAY MUNRO died at the age of 72 on the 29th December, 1925, at Edinburgh. He was educated at the Glasgow Academy and the Andersonian College. After early experience in telegraph work he made the instruments and erected the first practical telephone line in Glasgow in 1877. In the following year he invented and put on the market several forms of incandescent metal-filament lamps. Some of these were described in *Le Monde de la Science* of that year and in the *English Mechanic*. On the 1st May, 1880, he issued circulars relative to the formation of a telephone exchange in Glasgow, the proposed annual rental for subscribers being £5. By 1880 the Kelvin-street works of Messrs. Anderson and Munro were lit by Serrin lamps, and in that year also the firm installed arc lamps in, and in front of, the offices of the *Glasgow Herald*. This was described in that paper as the first application of electricity to street lighting in Glasgow. Early in 1881 Mr. Joseph Swan utilized Mr. Munro's dynamos to show Sir William Thomson and others his new carbon glow lamps, and in that year installations were fitted by the firm in factories at Selkirk and Hawick. Sir William's own house at the University was wired about this date and was later referred to by Lord Kelvin as "the first private residence on this planet to have electric light as the normal and sole illuminant." Among his patents in 1882 were lever switches, an integrating wattmeter and a gravity voltmeter and ammeter. These were followed by numerous others relating to dynamo windings, etc. In 1883 he invented and patented concentric wiring and applied this system to the wiring of the S.S. "Cavalier." He was soon busily engaged with water-power and gas-engine electrical installations all over the country. The Glasgow fire-alarm system was designed and fitted by his firm in 1885. In 1888 he designed and equipped the electric railway at Carstairs; this was for many years the only example of electric traction in Scotland. In 1892 Mr. Munro, who was then a recognized authority on hydro-electric work, was called to Norway to survey the Glommen and the Drammen rivers for the Christiania power scheme. He was responsible for much of the pioneer town-lighting in Scotland and was consulting engineer to the Kelvinside Electricity Co., the towns of Irvine, Lanark, Skelmorlie, Cambuslang, Galashiels, Bo'ness, etc., and designed and erected supply stations for the Glasgow and South-Western Railway Co., and the Clyde Trust and other public bodies. His design for the station at Kelvinside set for some years a new fashion in the lay-out of supply stations. In 1910 he severed his connection with the firm of Anderson and Munro and devoted himself entirely to his consulting work. During the war he was attached to the Royal Flying Corps and was officer in charge of the Portsmouth Group for the construction of seaplanes and flying boats. Mr. Munro was the author of numerous technical articles and papers. Being deeply interested in the complete reconciliation of science and theology he published two books "Spiritual Dynamics" and "The Divine Mechanism," both urging the application of a natural basis to religion. He was elected a Member of the Institution in 1890 and was one of the founders of the Glasgow Local Section (now Scottish Centre), the chair of which he occupied in 1905. D. S. M.

ERNEST ROBERTON MYERS received his general education at Mill Hill School, London, and his technical education at Owens College, Manchester, where he specialized in electrical engineering. He served his apprenticeship with the British Electrical and Manufacturing Co., Trafford Park, Manchester, and for a period of five years was constructional engineer in charge of the Manchester and Liverpool districts. During the latter period he was responsible for the carrying out of a number of large installations, including four turbo-alternators, auxiliaries and switchgear, at the Lister-drive power station of the Liverpool Corporation. He also installed motor-generators and switchgear at a number of the Corporation substations. In 1912 he received an appointment with Messrs. Balfour, Beatty and Co., Ltd., as electrical engineer in charge of a number of tramway undertakings controlled by that company. In 1920 he was appointed to the position of overhead lines superintendent of the Liverpool Corporation Tramways, and until the date of his death was responsible for the construction and maintenance of 160 miles of overhead lines. Since the time when he was appointed, many new routes have been opened, and he carried out all the necessary new work in connection with the overhead equipment. He was a man who took very great interest in his work, and his sudden death in June, 1925, was a great loss to the tramways undertaking and to his numerous friends, both in the Corporation and outside. He joined the Institution in 1908 as an Associate Member, and became a Member in 1924. P. P.

FREDERICK ALBERT NIXON died on the 3rd July, 1926, at the age of 60. He received his early education at All Saints' School, Bloxham, and when 17 years of age attended for two years at the City and Guilds of London Technical Institute, afterwards taking a three-year course at University College, London, studying mechanical and electrical engineering. In

1889 he went to the Brush Electrical Engineering Co. as a pupil, passing through the various departments of their works in London and Loughborough, including locomotive, stationary engine, dynamo work, and also spent some time in the drawing office. He was subsequently on the staff of the company, being employed on mains and station work in connection with a contract with the City of London Electric Lighting Co. In 1892 he was appointed third engineer at the Eccleston-place station of the Westminster Electric Supply Corporation, and was promoted subsequently to second engineer. In 1894 he was appointed superintendent of mains and underground work for this company under the direction of Dr. (now Sir) A. B. W. Kennedy, holding that appointment until 1897. In that year he was appointed resident engineer for Messrs. Kincaid Waller and Manville, in connection with the South London Electric Supply Corporation undertaking, becoming in 1899 chief engineer to that company. Later, as assistant to Messrs. Kennedy and Jenkin, he acted as resident engineer on the construction and equipment of the Greenhill electricity station at Oldham and was subsequently resident engineer for the Handsworth Urban District Council's electricity supply. In 1905 he was appointed chief engineer for this local authority's supply undertaking. In 1911 he received an appointment as engineer attached to the London staff of the Victoria Falls and Transvaal Power Co., Ltd., and when this company established an engineering department in London he organized the staff and was made head of the department, subsequently being appointed chief London engineer. During his 15 years' service with this company, Mr. Nixon was engaged upon important extensions to the Brakpan, Simmerpan and Rosherville stations. These extensions involved the installation of two 11 000 kW turbo-generators, three 12 500 kW turbo-generators, and three 7 135 kW turbo-compressors which, together with the boilers and auxiliaries, represented in the aggregate an additional 108 000 h.p. of plant. During 1922 the company, on the recommendation of its engineers in South Africa, decided to build a power station at Witbank, and in 1923 the work in connection with this station, which it had been arranged should be the property of the Electricity Supply Commission of South Africa, was started. The Witbank station consists of three turbo-generators, each of 20 000 kW capacity, with the necessary boilers, switchgear, transformers, pumping and other plant. Mr. Nixon, as chief London engineer, was in charge of the engineering work carried out by the company in London which, subject to the approval of Messrs. Merz and McLellan, the consulting engineers to the Electricity Supply Commission, comprised the negotiation, preparation and completion of contracts, designs, plans and specifications in connection with the establishment of the generating station and transmission lines, all the contracts for the plant being placed in the United Kingdom. The first section of the station went into commission on the 14th May, just about two months prior to his death. During the war he acted as manager and engineer to one of the Government explosive factories. He joined the Institution in 1889 as an Associate and was elected a Member in 1912. He was also a Member of the Institution of Civil Engineers.

SAITARO OI, a member of the second class of the Imperial Japanese Order of the Sacred Treasure, died on the 31st December, 1924, at Tokio, after a short illness. He was born in November, 1857, at Yamada, Miye Province, Japan, and graduated in May, 1882, after taking the electrical engineering course in the Imperial Japanese College of Engineering. He then obtained an appointment as an engineer in the Imperial Japanese Telegraph and Telephone Department, and later became head of the Department, a position which he held until his retirement in 1913. He joined the Institution as a Foreign Member in 1885 and was elected a Member in 1911. He was also a member of the Japanese Institution of Electrical Engineering and served for two years (1917–19) as president. I. N.

MARTIN FENN ROBERTS, who died suddenly on the 22nd February, 1926, was born at Lichfield in 1853. After studying at King's College, London, he entered the Engineering Department of the Post Office in 1871—the year following the transfer of the telegraphs to the State. In 1880 he was appointed Superintendent of Factories, and in 1898 an assistant engineer-in-chief. He retired from the Service in 1908 and subsequently, until his death, his extraordinary vitality and marked ability found outlet in the practice of a consulting engineer and as a director of Messrs. Henley's Telegraph Works, Co., Ltd. Throughout his career he was in close touch with all aspects of the design and manufacture of the wide range of materials in use in the Post Office and he aimed at, and spared no effort to secure, a standard of reliability and finish which was of the greatest possible value in establishing an efficient service of telegraph and telephone communications. He was quick to see the weak point of any design or scheme, but in his case the critical and the constructive faculties were equally well developed, and it was seldom that he was unable to contribute towards the solution of the many problems which presented themselves. From 1898 onwards Mr. Roberts, in association with Mr. (afterwards Sir John) Gavey, was responsible for the whole of the engineering work involved in the establishment of the Post Office London telephone system. The decision to provide the main channels of communication by means of underground plant produced many problems of a novel character, and to the solution of these Mr. Roberts contributed not only his sound engineering knowledge but also a degree of foresight which evoked the admiration of all who took part in that pioneer work—the foundation on which the present telephone system in London is based. Apart from his contribution to the purely telegraphic and telephonic side of Post Office engineering work, Mr. Roberts was for many years largely responsible for the considerable amount of mechanical and heavier electrical engineering work involved in the equipment of the Post Office factories and the provision of electric light, lifts, and heating and ventilating services in Post Office buildings generally, and it was from this standpoint that, in 1904 and, therefore, in the early days of three-phase transmission, he was deputed, together with the writer, to visit and report upon three-phase installations in Italy and Switzerland: this step was taken as a result of the decision to erect

the Post Office generating station at Blackfriars. In spite of his many professional interests, Mr. Roberts was by no means an engineer only: he was a lover of art and good literature—in particular of the poems of Keats and Shelley—and was himself a writer of more than average ability. Outdoors he was a keen yachtsman until in later years golf claimed his allegiance. During the war of 1914–18 he gave his services on the engineering side of the Ministry of Munitions. He joined the Institution as an Associate in 1874, and was elected a Member in 1887. He served on the Council in 1884-5.

J. M. G. T.

Captain MATTHEW HENRY PHINEAS RIALL SANKEY, C.B., C.B.E., R.E., son of the late General W. Sankey, C.B., was born at Menagh (Co. Tipperary) on the 9th November, 1853. He was educated at Morges and Schaffhausen, Switzerland; the Royal Military Academy, Woolwich, and the School of Military Engineering, Chatham. He received his commission in the Royal Engineers in 1873 and served in England, in Gibraltar, and, later, as Instructor in Fortification at the Royal Military College at Kingston, Canada. In 1882 he was appointed to the Ordnance Survey at Southampton in charge of the Trigonometrical Division, Electrotyping Department and Workshops, where he introduced the use of dynamos in the copperplate process of map printing. He described this process in a paper which he read before the Institution on "Electrolytic Deposition of Copper," and for which he was awarded the Fahie Premium. Another paper of his, entitled "A Problem relating to the Economical Deposition of Copper," gained the Paris Premium. In 1889 Captain Sankey retired from the Service and became a director of Messrs. Willans and Robinson, Ltd., continuing on the Board until 1904, when he took up consulting work. In 1909 he joined the boards of Marconi's Wireless Telegraph Co., Ltd., and the Marconi International Marine Communication Co., Ltd., of which companies he remained a director until the time of his death. A number of valuable books and technical papers are due to Captain Sankey. Among these are "The Energy Chart and its Practical Application to Reciprocating Engines"; Part IV Rimmington's "Building Construction" (published anonymously); translation from the German of Professor Ritter's "Bridges and Roofs"; the editing of the posthumous works of the late P. W. Willans on "Steam Engine Trials"; a paper on "The Thermal Efficiency of Steam Engines" for the Institution of Civil Engineers; a paper on "Governing of Steam Engines" for the Institution of Mechanical Engineers; and a series of papers on "Heavy Oil Engines" in the Howard Lectures for the Royal Society of Arts. In addition to the I.E.E. awards referred to above, Captain Sankey received the Telford Medal and Premium and the George Stephenson Medal of the Institution of Civil Engineers, and the Willans Premium of the Institution of Mechanical Engineers. He was a Past-President of the Institution of Mechanical Engineers and a Member of the Council of the Institution of Civil Engineers. He was also a Member of the Governing Board of the National Physical Laboratory, and of the Wireless Telegraphy and Gaseous Explosives Committees of the British Association. During the war he was Hon. Engineering Adviser to the Director of Fortifications and Works, and a member of the Hon. Valuation Committee, as well as of other war committees. Captain Sankey will be much missed by a large circle of personal and professional friends to whom he was known as an indefatigable worker with a great variety of technical interests on which he was actively engaged up to the date of his death, which occured suddenly at his home in Ealing on the 3rd October, 1925. He was elected an Associate of the Institution in 1885, and became a Member in 1886. In 1901 he served on the Committee of the Birmingham Local Section (now South Midland Centre).

A. G.

JOHANNES SCHUIL was educated in Holland and came to England during the latter part of the nineteenth century, and was for some time in the employ of the A.E.G. He later became the electrical engineer to the industrial establishments of the Salvation Army. In 1902 he joined the firm of A. Reyrolle and Co., Ltd., which had just recently been transferred from London to Hebburn-on-Tyne, in which place the remainder of his work was carried out. During the 19 years he was engaged by Messrs. Reyrolle he was responsible for the experimental and testing departments, and in addition was largely responsible for the design and development of several lines of the firm's manufactures, including a complete range of d.c. motor starters of the faceplate and drum types. The drum-type starter which he designed included an ingenious arrangement of interlocked double-pole automatic circuit breaker, as well as the well-known graphite resistance with current-growing characteristic. Other products which he developed while with the Reyrolle Co. were a line of tubular ventilated fuses, and flame-proof enclosures for fuses and motor starters. In 1921 he started business in Hebburn under the style of Schuil and Cullinan (which was subsequently altered to the J. Schuil Engineering Co.), manufacturing d.c. motor starters and other small parts. Towards the end of his business career he was engaged on the production of a form of oil-immersed metal-clad switchgear and high-voltage transformer for pressure-testing. He was elected a Member of the Institution in 1922, and was a regular attender at the meetings of the North-Eastern Centre, where he will be much missed by the members.

R. P.

GEORGE STEVENSON died on the 7th March, 1926, in the course of a journey to the Riviera where he was proceeding for the purpose of recuperating after a comparatively slight illness. His health had not been particularly good for a year or more, but his death at the early age of 49 was entirely unexpected. He commenced his engineering career as a student at the Royal Technical College, Glasgow, and his early practical training was obtained in the service of the London and Glasgow Engineering and Shipbuilding Co., and later with Messrs. Mavor and Coulson, also of Glasgow. In 1904 he became chief electrical engineer to the Carron Co., and, after a period of two years with that company,

joined the British Thomson-Houston Co., Ltd., as a sales engineer in their office at Glasgow. Remaining in that position until 1915 he became a very well-known figure in the electrical life of the great industrial district which surrounds Glasgow. He then was transferred to the Rugby works of the British Thomson-Houston Co., spending four years in the contract and export departments, and then, until June 1922, became an assistant to the commercial director of the same company in London. Finally, he joined the Chloride Electrical Storage Co., of Clifton Junction, as assistant sales manager, and remained with them in that position until the time of his death. Although the greater part of Mr. Stevenson's life was spent on the commercial side of engineering and electrical work, he was none the less a man of great technical ability. As a Member of the Institution he served on the Committee of the Scottish Centre and contributed technical papers at various times. He was also an Associate Member of the Institution of Civil Engineers. Throughout the whole of his business career he threw himself whole-heartedly into the service of the particular organization which employed him, and the fact that he never in any way spared himself probably led, in no small measure, to his early death. His passion for efficiency in others as well as in himself, made him a rigid upholder of discipline and gave him a seriousness of aspect in business affairs which belied his real kindly personality. To those who knew him best, he was a staunch friend and a charming companion, utterly unselfish and always concerned for the happiness and comfort of those around him. He became an Associate of the Institution in 1902, an Associate Member in 1904 and a Member in 1913. E. A. G.

BENTARA TAMAKI, a member of the fourth class of the Imperial Japanese Order of the Sacred Treasure, died on the 31st December, 1923, at Tokio after a long illness. He was born in November, 1859, at Kyoto, and graduated in May, 1883, after taking the electrical engineering course of the Imperial Japanese College of Engineering. On leaving the College he was appointed an engineer of the Imperial Japanese Telegraph and Telephone Department and subsequently served in the Testing Department. In 1890 he resigned his position to become an engineer of the Tokio Electric Light Co., but in 1895 again became a Government official as an engineer of the Imperial Japanese Communication Department. In December 1908 he was appointed head of the electrical department of the Imperial Japanese Railways, retiring in 1915. He was elected a Foreign Member of the Institution in 1888 and a Member in 1911. I. N.

LEONARD GEORGE TATE, general secretary of the Electrical Contractors' Association (Incorporated) and director of the National Electrical Contractors' Trading Association, Ltd., died on the 24th January, 1926, in his sixty-first year. His early training was with Pilsen Joel and the General Electric Engineering Co., which he joined in 1883. Here he came under the late Mr. Margary and Mr. Charles Robertson, of lamp fame. One year later Mr. Tate accepted the management of the lamp department of the Schuylar Electric Co. of Hartford, Conn., U.S.A., and remained in America for five years. In 1899 he was employed by the Brush Electrical Engineering Co., Ltd., under Mr. Dawbarn; and in 1892 joined Mr. Leslie Fuller in founding the business of Fuller and Tate, at 20 Bucklersbury, E.C., and it was this business which Mr. Tate carried on alone as Leonard G. Tate and Co., prior to associating himself wholly and whole-heartedly with the Electrical Contractors' Association. It may be said in all simplicity and sincerity that he devoted his life to the welfare of the British electrical installation trade. In all E.C.A. affairs he was an unfailing guide, philosopher and friend. As a man, he was upright, frank and true, and was loved and respected by all. He joined the old National Electrical Contractors' Association in 1902 and was soon afterwards elected to the "Managing Committee." In this capacity he assisted in the incorporation of the E.C.A. and in the formation of its present constitution. In 1905 he accepted the position of hon. secretary to the Incorporated Association, and in this capacity he continued to act until 1918, when he severed his connection with the firm of Leonard G. Tate and Co. and became the whole-time general secretary of the E.C.A. Allied Associations. On the occasion of the E.C.A. Annual General Meeting held in June, 1925, the Allied Associations presented Mr. Tate with a silver salver and cheque "as a token of esteem and mark of appreciation for the valuable services rendered by him during the past 21 years." He joined the Institution as an Associate Member in 1902, and became a Member in 1924. R. W. K.

JAMES HAY THOW died in his fifty-ninth year on the 22nd April, 1926, after a short illness. He entered the Post Office Engineering Department as a telegraphist at Glasgow in October, 1884, and was transferred in March, 1892, to the engineering branch, in which department he passed through the grades of junior clerk, second-class clerk, and first-class clerk prior to 1897 when he became a second-class engineer. In 1902 he came to London as a first-class engineer in the (then) South Metropolitan District, and took charge of the Ealing Exchange area when the Ealing Exchange was opened in 1904. After some years in charge of the Western Exchange Section he was engaged for a short time in the Technical Section of the Superintending Engineer's Office, and was then transferred to the Central Telegraph Office Section. In this Section he took a very active interest in the Dudley pneumatic tube (continuous suction, low vacuum) system, and made many attempts to solve some of the difficulties inherent in the street tube system in London, but his experiments came to a close on his promotion to Assistant Superintending Engineer in the South Midland District, with headquarters at Reading. During the war, he took special charge of the installation and maintenance of works in connection with air defence in the South Midland District, with headquarters at Reading. After the war extensive underground works, including the South Midland District portion of the London–Bristol, London–Southampton, and a number of the London toll cables,

were mainly under his control. In 1922 he was transferred to the London Engineering District where he dealt more particularly with telegraph matters, buildings, and the technical training of the minor staff. His interests and hobbies were many. At Ealing he was well known in local circles and for many years was a member of the choir of the Parish Church. On his return to London from Reading he lived at Tulse Hill and became a member of the church choir there. In all, his services as a chorister extended to 50 years. Mr. Thow was a very capable amateur mechanic and was skilled in the use of tools. He was also expert in cabinet making and wood working, and his work would be creditable to a professional craftsman. He possessed an exceptionally bright and cheerful personality, and was popular with all grades of the staff. He was a devoted husband and father, and those who knew him intimately mourn the loss of a sincere friend. An indication of the love and respect of those with whom he came in contact is contained in the fact that upwards of 200 letters of condolence were received by his family. He was elected a Member of the Institution in 1922.

R. A. W.

ALEXANDER WYLLIE died on the 5th June, 1925, at the age of 55. He was born in Adelaide, South Australia, and came to England to receive his technical education. His first appointment was as borough electrical engineer of Walsall, and in 1907 he resigned that position to go to Auckland, New Zealand, as the city electrical engineer. The first section of the plant was installed in 1908, and when further additions were planned in 1920 Mr. Wyllie re-visited this country, where he purchased most of the necessary machinery. In 1922, when the control of the city electric supply was vested in the newly-constituted Auckland Power Board, he was appointed general manager. He was elected a Member of the Institution in 1905.

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EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the general title or subject of a paper or address.
(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.
(D) indicates a reference to a discussion upon a paper or address of which the general title or subject is quoted.
(d) indicates a reference to a subject dealt with in a discussion on a paper or address of which the general title is not quoted.

A.

D.

I.

J.

MOTORS, ELECTRIC.

V.

W.

X.

Y.

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